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A Camera with adaptive Photoreceptors in analog CMOS Technology

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ABSTRACT

A system of adaptive photoreceptors has been designed and built in a standard CMOS process. The mechanism of adaptation is based on an analog feedback circuit modelled after the biological example. The system exhibits a large dynamic range of approximately 7 orders of magnitude in light intensity and a pronounced capability to detect moving objects. Simulations and measurements with single adaptive receptors as well as first experiences with a camera system are presented.

1 CONCEPT

The *Complementary Metal Oxide Silicon (short : CMOS)* technology plays a major role for mass production of integrated circuits. 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. 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 realised 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 realisation of a biologically motivated adaptive photoreceptor based on an analog feedback circuit. The system and its properties are described in more detail in.[1]

2 BIOLOGICAL MODEL

Fig. 1 shows the measured membrane potential of a turtle cone (red sensitive) as measured by Normann and Perlman.[2] 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).

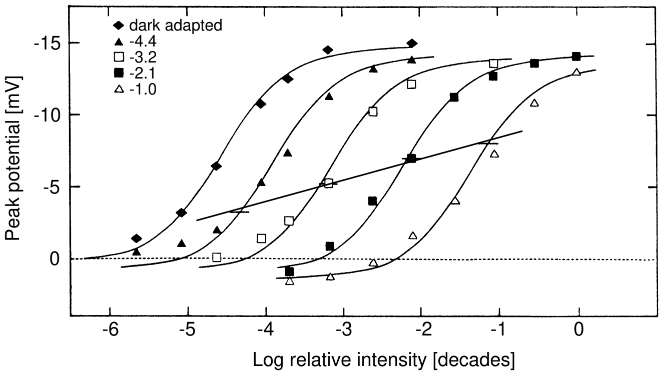

Figure 1: Response curves of red sensitive cones in the turtle retina.[2] The measured membrane potential (relative to the dark potential represented by the dotted line) is plotted as a function of the intensity of the incoming light. The 0. decade corresponds to an intensity of about 20 W/m^2. The full 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 REALISATION

3.1 Electronic realisation of an adaptive pixel

The circuit for the adaptive photoreceptor described here closely follows the suggestion by T. Delbrück and C. A. Mead.[3] The circuit is shown in Fig. 2. 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.

The input stage of the receptor consists of a reverse biased photodiode and a feedback transistor $\mathrm{M_{fb}}$. Typical incident illuminations correspond to diode photocurrents in the range of pA to nA. This causes the feedback transistor $\mathrm{M_{fb}}$ to operate in the subthreshold region. As a consequence the source voltage V_s is proportional to the logarithm of the photocurrent I_{ph}. The gate-source voltage between the potentials V_{cap} and V_s settles to a value required to deliver the current needed by the diode. The voltage V_{cap} is stored on the capacitance C_1 and acts as a model for the input intensity.

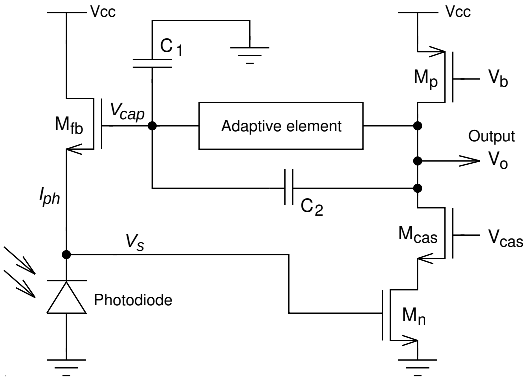

Figure 2: Circuit of the adaptive photoreceptor.

The comparison between input signal and model prediction is carried out by the inverting amplifier formed by the transistors $\mathrm{M_p}$ und $\mathrm{M_n}$. The voltage V_s regulates the current flowing through $\mathrm{M_n}$. The current through the p-MOS-transistor $\mathrm{M_p}$ is set by the external bias voltage V_b. The voltage gain v_{amp} is given by the ratio of the output impedance of the amplifier and the impedance of $\mathrm{M_n}$. The gain value is determined by the lengths of the transistors. Typical values are in the range of 1000. The additional cascode transistor $\mathrm{M_{cas}}$ increases the drain impedance of $\mathrm{M_n}$ and leads to a further increase of the voltage gain. In addition the amplifier gets faster. $\mathrm{M_{cas}}$ protects the drain of $\mathrm{M_n}$ such that the gate-drain capacitance of $\mathrm{M_n}$ is only exposed to small voltage changes. In consequence the input voltage V_s needs to drive only a small capacitance. The output signal V_o is fed back over the *adaptive element* and a capacitive divider formed by $\mathrm{C_1}$ und $\mathrm{C_2}$ to the gate of the feedback transistor $\mathrm{M_{fb}}$.

The adaptive element consists of a p-MOS-transistor with a short circuit between drain and gate and a parasitc bipolar pnp transistor with two collectors. One collector ist connected to the base and the other is formed by the subtrate which is on ground potential. The system basically acts like two parallel connected diodes with opposite polarity. Independent of its direction the current rises exponentially as a function of the applied voltage. For small voltages the system corresponds to an extremely large resistor with a value of typically $10^{12}\ \Omega$. This value is essential to obtain a long RC time constant with the small capacitors available in VLSI technology. The realisation of the adaptive element for this project follows closely the description in.[3]

The adaptation mechanism works in the following way : A small increase of the photocurrent I_{ph} tries to pull down the voltage V_s. The output voltage V_o reacts with an increase given by the voltage gain v_{amp}. At the same time the output voltage is fed back through the capacitive divider to the gate of the feedback transistor $\mathrm{M_{fb}}$. In consequence the voltages V_{cap} and V_s move up. Hence the the feedback mechanism acts to compensate the initial perturbation such that V_s is held almost constant. For slow changes the gain of the receptor is small because the feedback takes place across the large but finite resistor formed by the adaptive element. For rapid changes however, no current can flow across the adaptive element and the changes are transmitted to the gate of $\mathrm{M_{fb}}$ via the capacitive divider. This causes a damping of the feedback signal and hence requires a larger reaction of the output voltage V_o in order to keep V_s at a constant value. The gain of the circuit to transient signals is given by the ratio of capacitances in the divider. The larger $\mathrm{C_1}$ relative to $\mathrm{C_2}$ the larger the gain is.

3.2 CMOS LAYOUT

Based on the adaptive circuit described in the previous chapter a CMOS chip has been designed and produced. The 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. 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.

Fig. 3 shows a microphotograph of the produced chip. The picture demonstrates the basic structure of the chip which has a size of 3.5×2.5 mm^2. The layout is divided into two separate structures. 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.

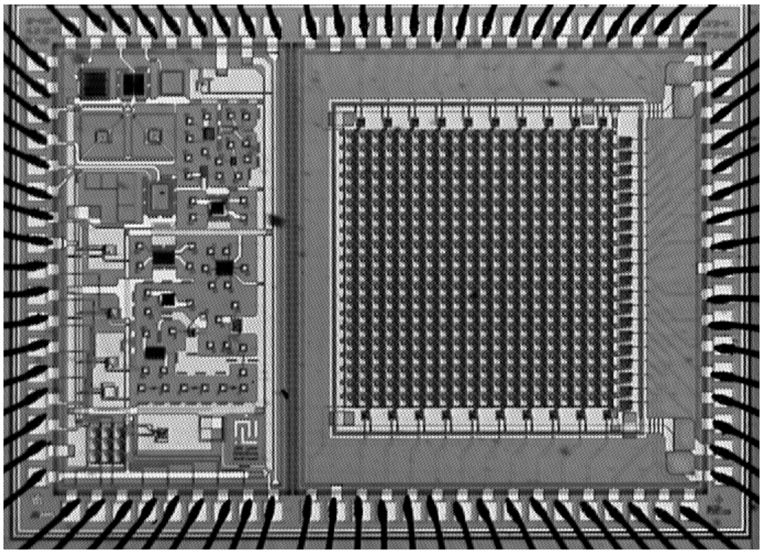

Figure 3: Microphotograph of the produced vision chip

The layout of a single adaptive pixels occupies a surface area of approximately 50×50 μm and is shown in Fig. 4. It is dominated by the capacitive divider formed by C_1 and C_2. The capacitors are build from two polysilicon layers. At the top edge of the pixel design the quadratic shape of the n^+-substrate photodiode can be seen. 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 diode has been realised as a geometrical extension of the source area of the feedback transistor M_{fb} since source and drain of an n-MOS transistor are made of n^+-diffused material. The photodiode itself has a surface area of 15×15 μm^2. The remaining analog processing electronics is located at the right side of the pixel layout. 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 most critical part in terms of sensitivity to light is the adaptive element. For this reason it has been placed at maximum distance from the photodiode. This way only few scattered photons or diffusing charge carriers can reach the adaptive element.

The footprint of the chip is dominated by a matrix formed by 20×20 photoreceptors. 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 like the adaptive element 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. Digitisation is carried out

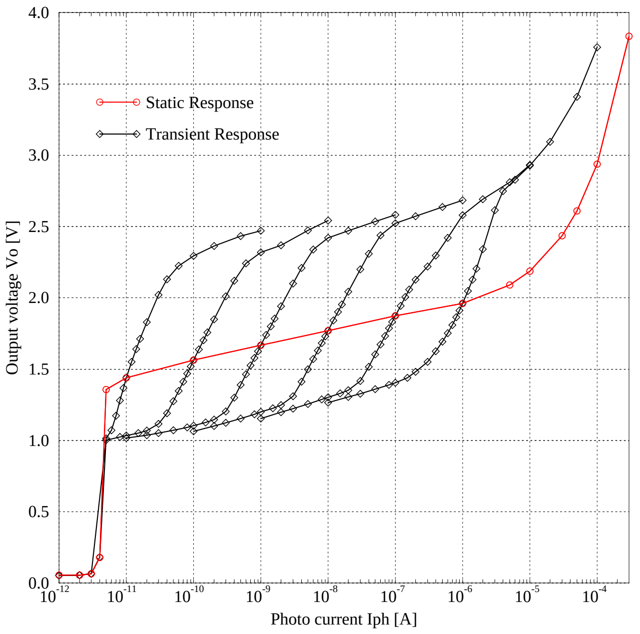

Figure 5: Simulation of the response of the adaptive photoreceptor.

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. 5 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 with adaptive pixels

Measurements with the produced adaptive pixels have been carried out over a large range of input intensities corresponding to 11 decades. 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 controlled scanning table to a precision of 1 μm. An absolute calibration of light intensities was provided by a photometer. Fig. 6 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. 5 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 capacitive divider and in turn the transient gain. A few testpixels on the chip have been equipped with different ratios in the capacitive divider. A ratio of 3 : 1 instead of 10 : 1 in the standard pixel reduces the transient slope to about 300 mV per decade. This leads to a slope ratio of 15 : 1. The standard pixel is therefore characterised by a very pronounced sensitivity to motion.

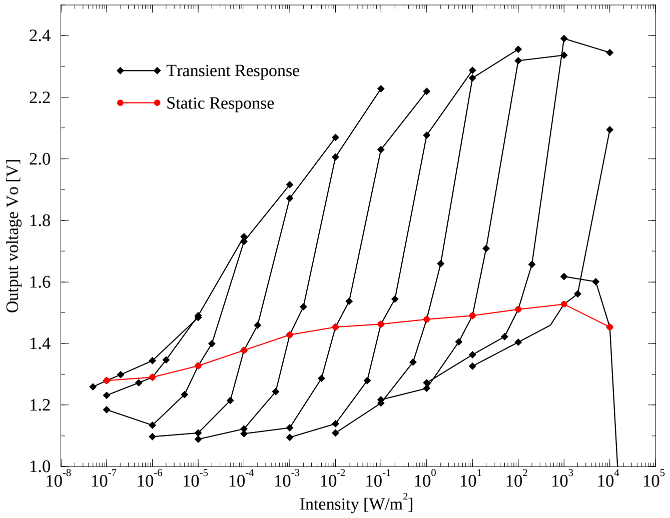

Figure 6: Measured response of the adaptive photoreceptors over 11 decades of incident illumination.

This effects is desirable for the envisaged application (see last chapter) and has been demonstrated with the camera system (next chapter).

Fig. 7 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 element. Light penetrating through the metal shield generates a parasitc photocurrent which leads to a faster discharge of the storage capacity C_1 and in turn causes 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 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 on 2 chips. 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 digitisation by a calibration algorithm.

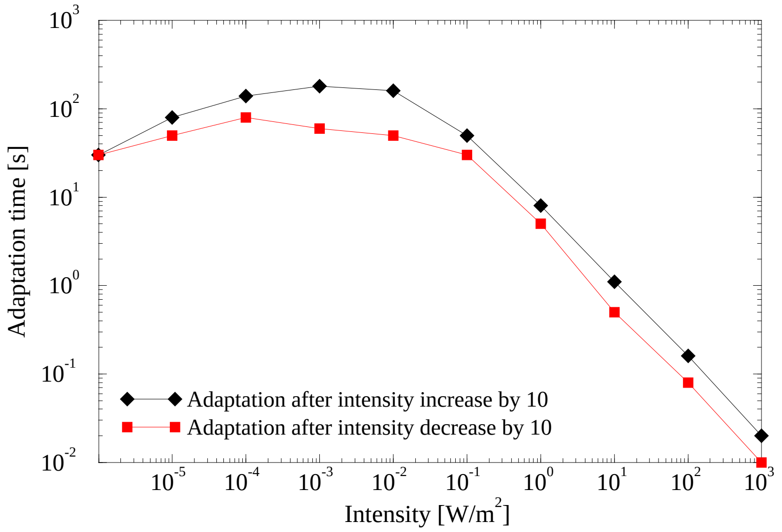

Figure 7: Adaptation time as a function of incident illumination.

4.3 Experiences with the adaptive camera system

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 digitised 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 digitised data have been implemented.

Fig. 8 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. 8. 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 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. This example demonstrates the capability for motion and edge detection with an adaptive camera system. Various scenes recorded outside the laboratory have also shown the possibility to detect moving cars, pedestrians and other moving objects.

5 APPLICATION AND FUTURE 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

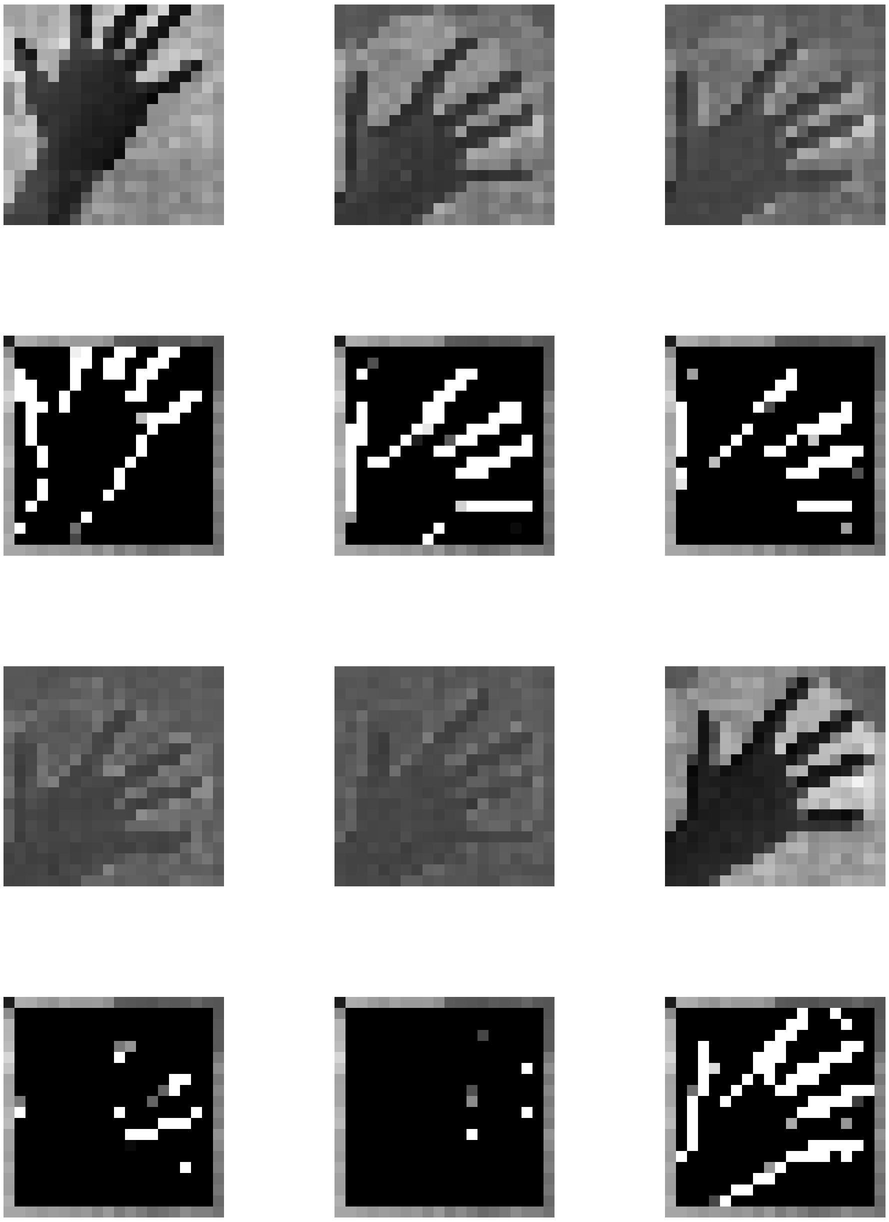

Figure 8: Simple moving object recorded with the adaptive camera. The first and the third row show a sequence of pictures recorded with the adaptive camera system. A hand is moving into the picture and held in position for a while. After pixel adaptation the hand is moved again and appears on the picture. The second and the fourth row show the output of a digital edge detection algorithm.

pronounced capability of motion detection together with conventional edge detection algorithms in an application as a tactile vision aid for the blind. After reducing the image to the information about edges of moving objects the data will be transferred to the skin of a person with the help of mechanical actuators.[5] A highly compact adaptive vision system with improved space resolution and integrated signal processing is in preparation.[6]

6 REFERENCES

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