An Analog VLSI Velocity Sensor

Jörg Kramer, Rahul Sarapeshkar and Christof Koch

California Institute of Technology
Computation and Neural Systems 139-74
Pasadena, CA 91125
phone: (818) 395-2874
fax: (818) 796-8876
e-mail: kramer@cns.caltech.edu

ABSTRACT
An integrated circuit that computes the velocity vector of a visual stimulus in one dimension is presented. The circuit combines optical sensors and associated electronics on a single silicon chip, processed with standard CMOS technology. The velocity is inferred from the time delay of the appearance of an image feature at two fixed locations on the chip. The circuit operates quite robustly for high-contrast stimuli over considerable irradiance and velocity ranges. With lower-contrast stimuli the output signal for a given velocity tends to decrease, while the direction selectivity is still maintained. The individual motion-sensing cells are compact, and they are therefore suited for use in dense 1D or 2D imaging arrays.

I. INTRODUCTION
Various applications in robotic guidance and remote sensing require small, fast, sensors for the processing of visual motion. Robust measurement of velocity in real time is a difficult task, but necessary if a system has to operate in dynamic environments. Parallel processing at each image location is best suited to handle the large volume of incoming irradiance data from the optical sensors. The processed output should neither depend on irradiance nor on contrast. However, because physical systems are always subject to the presence of noise, the output is a function of these parameters, even in high-performance biological systems like the fly.

In this article, an elementary sensor for the determination of 1D velocity in real time is reported. It is constructed by combining photoreceptors with analog electronic circuitry on a single silicon substrate using CMOS VLSI technology. Analog integrated circuits do not attain the precision levels of digital circuits, but they are better suited to meet the criteria of compactness and low power consumption. Parallel processing and real-time operation are achieved by building arrays from these elementary motion sensors. Previous attempts at implementing 1D or 2D motion sensors with analog VLSI technology have been made [1-4]. None of these circuits outputs a signal that unambiguously encodes velocity independently of image brightness and contrast over typical ranges encountered in natural scenes.

The circuit presented here exhibits a monotonic dependence of the output signal on the 1D stimulus velocity. It operates robustly over large speed and illumination ranges. It is more compact and responds to lower contrasts than most previous implementations. It uses the architecture schematically illustrated in Figure 1. At each pixel location, a quick irradiance transient is converted into a short current spike by a temporal edge detector (E). This current spike is transformed into two different voltage pulses by a pulse shaping circuit (P). Each one of these voltage pulses, together with the other voltage pulse...
of the adjacent pixel, is fed into a motion circuit (M) that responds to one direction of motion; the pair of motion circuits responds to both directions of motion. Note that a single motion sensor in a 1D array contains a pair of motion circuits, but only one edge detector and one pulse shaping circuit; this is so, because the pulse outputs are used by neighboring motion sensors as well.

II. TEMPORAL EDGE DETECTOR

The motion sensor uses a temporal edge detector as an input stage. At each pixel site a rapid increase in brightness is converted into a short current spike. This corresponds to detection of temporal dark-bright or ON edges. The circuit schematic is shown in Figure 2.

![Fig. 2. Circuit diagram of the edge detector, consisting of a photoreceptor, and a "haircell" with amplification, differentiation, and rectification.](image)

The adaptive photoreceptor (Q1–Q4) was developed by Delbrück [3]. Its output voltage $V_{ph}$ increases logarithmically with irradiance of the photodiode, as long as the MOSFETs are operated below threshold. Thus, a transient $dE$ in the image irradiance $E$ causes a voltage transient $dV_{ph}$ that is only a function of contrast $dE/E$. This property is highly desirable for the extraction of local features from an image, because the overall illumination of a typical scene is likely to change with time. The transient step response is higher than the adapted DC response by $(C_3 + C_4)/C_4$, the inverse of the capacitive divider gain in the feedback loop. The I-V relationship of the adaptive element Q4 is that of a sinh. Consequently, the adaptation is slow for small output voltage steps and fast for large steps. With $(C_1 + C_2)/C_2 = 10$, adaptation time constants of several seconds were obtained. In subthreshold operation, the transient change of the photoreceptor output voltage to an irradiance step is given by

$$dV_{ph} = \left( \frac{kT}{q} \right) \left( \frac{C_1 + C_2}{C_2} \right) \left( \frac{dE}{E} \right) \quad (1)$$

where $kT/q$ is the thermal voltage and $\kappa$ is the back-gate coefficient of Q1.

The output of the photoreceptor is fed into a circuit that transduces positive voltage excursions in the photoreceptor voltage, corresponding to ON edges, to a current. The transistors Q5–Q13 comprise a wide-range operational amplifier with a bias $V_b$, connected to some other transistors (Q14–Q17) and capacitors (C3–C5), so that it is in a non-inverting feedback configuration. The capacitors C3 and C4 form a capacitive divider that causes the gain of $V_{int}$ to be $(C_3 + C_4)/C_4$ with respect to the input voltage $V_{ph}$ of the amplifier. The adaptive element Q14 is a sinh element, identical to that used in the photoreceptor, that prevents the $V_-$ node of the amplifier from floating by slowly adapting it to $V_{int}$. The current charging the node $V_{int}$ is given by

$$I = C_{tot}dV_{int}/dt, \quad (2)$$

where

$$C_{tot} = C_3 + \frac{C_3C_4}{C_4 + C_4} \quad (3)$$

if we make the assumption that Q14 is only weakly turned on. This current is supplied by Q16 if it is positive and by Q15 if it is negative. The transistor Q15 is source-connected to minimize body-effects, since the DC voltages of operation are around 1.5 V. If we sense the current in Q16 with the diode-connected Q17, $V_{out}$ may be used to mirror copies of it to succeeding circuits. The voltage $V_g$ may be used to set the gain of this output mirror if it is operated within a few mV of $V_{DD}$. The circuit thus serves as a differentiating, amplifying, and half-wave-rectifying element all-in-one. It is a functional analog of auditory hair cells that sense the motion of the basilar membrane in the cochlea. Here, it is used to sense voltage changes in the photoreceptor output caused by irradiance increases. Using (1)–(3) we can calculate the net output current as

$$I = C_{tot} \left( \frac{C_3 + C_4}{C_4} \right) \left( \frac{C_1 + C_2}{C_2} \right) \left( \frac{kT}{q} \kappa \frac{dE}{E} \right) \frac{dE}{Edt}. \quad (4)$$

The output current is therefore proportional to the temporal contrast $(\frac{dE}{Edt})$. The temporal contrast is the product of the velocity $v$ and the spatial contrast $(\frac{dE}{Edx})$

$$\frac{dE}{Edt} = v \frac{dE}{Edx}. \quad (5)$$

III. PULSE SHAPING CIRCUIT

The circuit shown in Figure 3(a) is a nonlinear version of a differentiator constructed by having a low-pass filter in the feedback path of a high-gain amplifier. The transistors Q20–Q22 and capacitor C function as a source-follower-like low-pass filter; the high-gain amplifier is formed by
Q_{18} and Q_{19}. The input to the circuit is a current $I$, obtained from the mirror constructed by connecting the output voltage of the edge detector ($V_{out}$ in Figure 2) to $V_{in}$ of the filtering circuit. The voltage $V_s$ responds to an input current spike from the edge detector with a voltage spike. The voltage $V_s$ responds to the same spike with a sharp onset and a log(t)-like decay. The input $I$ may be thought of as an impulse that sets the initial condition on the diode-capacitor subcircuit of $Q_{21}$, $Q_{22}$, and $C$. It may be shown that, for an initial condition with a spike height of $I_{in}$, the diode-capacitor current $I_{out}$ is given by

$$I_{out}(t) = \frac{I_{in}}{1 + \frac{I_{in}}{CV_C}}$$

where

$$V_C = \frac{kT(\kappa + 1)}{qR^2}.$$  

The voltage $V_C$ obtained by using two stacked diodes is larger than that obtained by using one diode, and serves to increase $V_f$ and $V_s$. After a sufficiently long time $t$, such that $I_{in}t \gg CV_C$, $I_{out}(t) \sim CV_C/t$ and $V_s(t) \sim CV_C \log(t)$, i.e. $I_{out}$ and $V_C$ are independent of $I_{in}$. Conversely, at a given time $t$, $I(t)$ \sim $CV_C/t$ if $I_{in}t \gg CV_C$. We shall explain in section IV how we exploit this property to make our velocity output independent of contrast, if the contrast is sufficiently large. Note that a diode-capacitor configuration intrinsically adapts to time constants over many orders of magnitude. Therefore, the circuit has no explicit time constant determined by a bias voltage, nor does it have an explicit threshold for the value of $I_{in}$ where contrast-insensitivity begins.

![Fig. 3. Circuit diagrams of (a) the pulse shaping circuit generating two voltage pulses $V_f$ and $V_s$ in response to a current pulse $I$, and (b) a pair of motion circuits computing speed in opposite directions. The voltage terminals $V_{ph}$ and $V_{amp}$ refer to the outputs of one pulse shaping circuit, while $V_{ph}$ and $V_{amp}$ refer to those of the other one, as indicated in Fig. 1.](image)

**IV. MOTION CIRCUITS**

For the computation of the velocity of a stimulus the analog voltage of the slowly decaying pulse $V_s$, initiated at one pixel is sampled by the voltage spike $V_f$ triggered at an adjacent pixel. For the determination of a signed velocity component, two such sample-and-hold circuits are necessary (Figure 3(b)); this is so because each circuit can only determine speed for the direction of motion where the $V_s$ pulse is initiated before the $V_f$ spike. This direction is called the preferred direction. Since the $V_s$ pulse facilitates the measurement, we call the algorithm facilitate-and-sample (FS). The monotonic decay of the facilitation pulse ensures unambiguous encoding of speed in the sampled voltage. In the other direction, called the null direction, the sampling pulse precedes the facilitation pulse and the voltage of the facilitation pulse triggered by the previous edge is sampled. The latter voltage is normally low unless edges arrive in quick succession. The FS circuit responds down to arbitrarily slow speeds, while showing good sensitivity at high speeds. Under the assumption that $I_{in} \Delta x/v \gg CV_C$, where $\Delta x$ is the pixel spacing, the sampled output voltage $V_{out}$ is independent of $I_{in}$ and is given by $V_{out} \sim CV_C \log \left( \frac{\Delta x}{v} \right)$. The sensitivity $dV_{out}/dv$ is highest at slow speeds, decaying with $v^{-1}$. A single element of our velocity sensor consisting of a temporal edge detector, a pulse shaping circuit, and two motion circuits comprises 34 transistors.

**V. EXPERIMENTAL RESULTS**

The FS motion sensor was fabricated using a 2 $\mu$m n-well CMOS process provided by MOSIS. An elementary
motion cell covers an area of 0.05 mm². The imaging lens used for circuit testing has a focal length \( f = 13 \) mm and an f-number of 1.6. For quantitative measurements, sheets of paper with printed gray scale patterns were wrapped around a rotating drum to provide the optical stimuli. The object distance was set to 380 mm. Measurements were taken under incandescent room lighting conditions, where a white paper surface provided an illuminance of about 1.2 lux on the chip. Figure 4 shows the response of the different stages of the circuit to a black moving bar on a white background. The 120 Hz flicker noise can clearly be seen on the output voltage trace \( V_{out} \) of the wide-range amplifier. The bias of the operational amplifier \( V_b \) was set at low gain (low \( V_b \)) so that the flicker noise remained tolerable.

The response curves for the preferred direction at different global illumination levels are shown in Figure 5. The proximity of the curves to each other is a result of the good contrast encoding of the photoreceptor. Robust operation was observed down to very dim room illumination levels. In Figure 6, the effect of using different edge sharpnesses and contrasts under standard room lighting conditions is shown. The decrease of the response at relatively high contrasts is due to the fact that the input stage had to be operated at low gain in order to suppress flicker noise. Experiments with DC illumination show that a 40% contrast sinusoidal stimulus can be made to yield almost the same response as a 100% contrast bar stimulus.

VI. CONCLUSION

An algorithm for the measurement of velocity in one dimension and an implementation with analog circuitry using CMOS VLSI technology was presented. The circuit is more compact and more reliable than any previously reported analog single chip velocity sensors, the authors are aware of. It operates robustly even more than one order of magnitude in velocity, is contrast-invariant for sufficiently high contrasts while gradually degrading at low contrasts, and works down to dim room light levels.

ACKNOWLEDGMENT

This work was supported by grants from the Swiss National Science Foundation and the Office of Naval Research. Fabrication of the integrated circuits was provided by MOSIS.

REFERENCES


