Measurement of Fast Rotation by VLSI Circuits

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Abstract. There exist important problems that require the measurement of very fast motion. Common techniques for motion estimation based on sequences of video images usually fail to deliver the correct results for such problems due to the low video rate. We present an analog VLSI based system that determines the motion in real-time. We demonstrate the performance of that system for the case of measuring the rotation speed of a fast rotating platform.

1 Introduction

The most important source of information for many animals is sight. Not surprisingly, interpretation of visual information acquired usually by video cameras ("machine vision") is as important for artificial systems. The typical frame rate of common CCD video cameras lies in the order of 30 frames per second, although there exist high-speed cameras acquiring up to 40.000 frames per second. The use of these cameras is quite limited due to high cost and the problem of analyzing the huge amount of incoming data in time when real-time performance is required.

Although sufficient for most applications, the standard 30 frames per second frame rate is not high enough for some interesting problems, e.g., measuring the rotation speed of a rotating camera (this is a special case of stabilizing a shaking camera). A typical optical system with a wide angle lens has a field-of-view of about 45° in diameter. Given a 512 by 512 CCD sensor, one image pixel corresponds to approximately 0.1° . If such a system rotates with e.g. 90° per second and images are captured at standard video rate, the image will be displaced by about 30 image pixels between consecutive frames. Determining the motion in such fast moving images is usually not possible when correlation based methods are used due to limited available computing power.

It is hence desirable to have an affordable system that is capable of determining motion in a velocity regime considerably above the limit imposed by common video cameras.

2 The proposed system

We propose to use a system designed in analog VLSI technology that performs the necessary measurements in real time. In the following we will demonstrate how such a system can be utilized in the task of recovering rotation speed of a turning platform.

The used sensors are integrated circuits built in 1.2μm VLSI technology with on-board photoreceptors and processing stages that have been designed in our group in the last years. The sensor has been developed by Kramer et al. [KSK97, IKK96] and is described in more detail in section 3.

In order to measure the rotation speed of the platform, the task is to find the motion in the horizontal plane. It is therefore not necessary to determine a two-dimensional velocity vector, a one-dimensional motion measurement is sufficient. Although actually only one sensor is required to compute the one-dimensional motion signal (since the perceived motion should be the same no matter in which direction the sensor is oriented), it is preferable to use a number of sensors analyzing the visual input from different directions. This allows for improving the accuracy of the overall measurement by averaging over all sensors. Furthermore the system's response will be more robust since it will always provide reliable information which would not be the case if the only sensor of a system at a certain time happened to point in a direction where no motion can be estimated (e.g., due to missing texture or too low contrast).

To obtain visual information from many directions, several ways exist to arrange the sensors: they can be either circularly arranged, facing outwards, or facing up, using a conical mirror (see figure 1). Such setup has been successfully used by another group in a different project [FSG$^+$96].

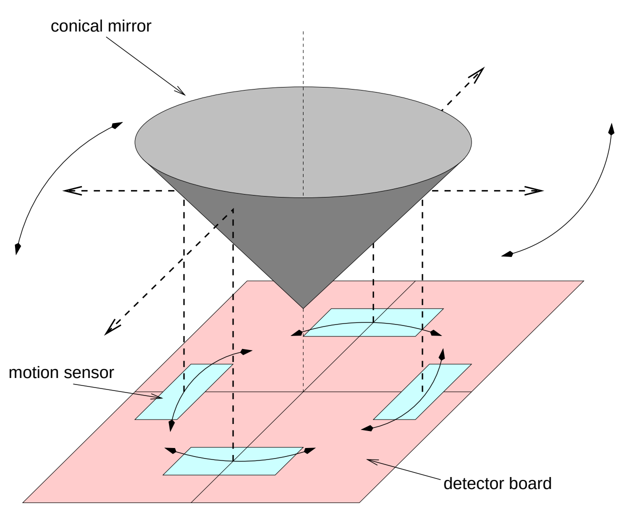

Fig. 1. Obtaining information using a rotating platform with a conical mirror.

In either way, the problem remains to analyze one-dimensional motion. In case of a setup with a conical mirror, it is possible to use one multi-sensor circuit with a circular array of sensors instead of a circular array of sensors as shown in the figure. This of course requires the design of more sophisticated sensor circuits which are described in section 3.2. Such sensors are currently in fabrication.

Since all three discussed setups (circular arrangement of sensors facing up or outward, and a single multi-sensor chip) are qualitatively equivalent in terms of determining the speed of rotation by one-dimensional motion analysis, we will demonstrate the performance of our one-dimensional motion detectors in the section 4.

3 Analog VLSI motion sensors

3.1 Background

Photosensitive analog integrated circuits are superior to conventional CCD-μP systems in many respects:

- By making use of the intrinsic physics of MOS transistors and capacitors functions like adding, subtracting, multiplying, dividing, raising to arbitrary powers and exponentiating of signals are easily implemented with no more than a few devices [Mea89]. Versatile spatio-temporal filters are readily achieved, too. As a result many identical computing units ("pixels") can be implemented on one chip, the operation of which is fully parallel and no analog to digital conversion is needed.
- The sensors consume very little power (tens of milliwatts) because the MOS transistors are used so that only very small currents flow (1pA to 100nA).
- By using a standard 1.2μm CMOS process to fabricate the chip and because no additional external circuitry is needed the sensing system is very compact, light-weight and inexpensive.
- Because we use CMOS compatible photosensors with non destructive readout [DM94] we are able to implement the sensing and computing elements on the same chip. Thus no external camera is needed and the computation is performed in real time.

3.2 Velocity measurement with analog VLSI chips

Algorithms for velocity detection can be categorized into two groups: gradient based and correlation based methods. Using analog VLSI technology we have successfully implemented instances of both methods into single chip sensors.

Gradient based sensors We combine the gradient constraint equation [HS81]

$$\nabla I(\mathbf{x},t) \cdot \begin{pmatrix} v_x \\ v_y \end{pmatrix} + I_t(\mathbf{x},t) = 0 \tag{1}$$

with the additional constraint to only determine the normal flow. As can be shown, the velocity components in both spatial dimensions are thus described by the expression

$$v_x = -\frac{I_t I_x}{I_x^2 + I_y^2}, \qquad v_y = -\frac{I_t I_y}{I_x^2 + I_y^2}. \tag{2}$$

We developed a sensor that computes these expressions in parallel and in real time. This sensor is currently in fabrication. A working sensor that weights the velocity components with a confidence measure is presently being tested.

We also designed a sensor particularly suited for measuring rotation velocity. This is achieved by circularly arranging the pixels on the chip. Each of the pixels computes the one-dimensional case of expression (2) which is given by

$$v = -\frac{I_t}{I_x}. \tag{3}$$

The layout of this chip is shown in figure 2:

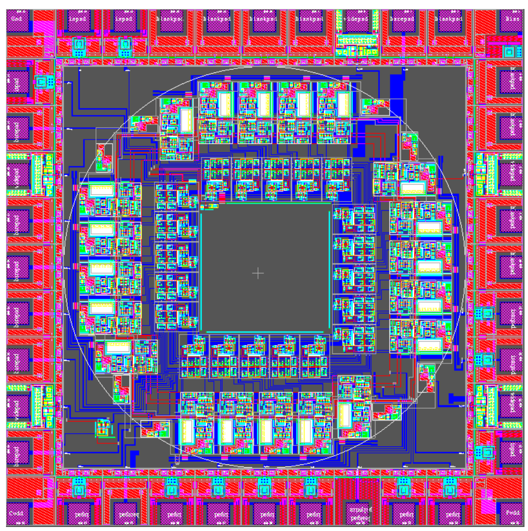

Fig. 2. Layout of the VLSI circuit with circularly arranged pixels

Correlation based sensor One particularly successful instance of a correlation-based sensor is the Facilitate and Sample ("FS") chip developed by Kramer et al. [KSK97, IKK96]. The principal idea of this approach is to measure the time of travel for a feature moving past the sensor, which is illustrated in figure 3;

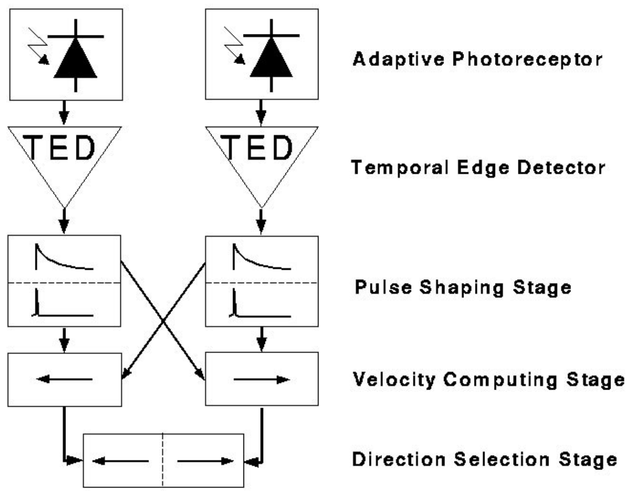

Fig. 3. Two FS sensor cells in the 50 cell array

Temporal edge detectors (TED) generate a pulse in response to a fast image brightness transient. The pulse shaping stages convert this pulse into a fast voltage spike and a slowly decaying voltage signal. The latter signal is fed into the neighboring pixels. With the fast voltage spike the slowly decaying signal is sampled and held in the velocity computing stage. The lower this held voltage is, the slower the velocity of the edge was. The direction selection stage suppresses the null direction velocity output by taking the maximum of both directions.

For the measurements presented in this paper we are using a one dimensional FS array of 50 pixels with averaged velocity output.

4 Results

First the sensor's response to a simple test pattern was measured to provide data for comparison. Therefore a circular wall with vertical black and white bars on the inside was placed around the rotating sensor. The sensor's output was recorded and averaged over time while the sensor rotated. The expected curve for the sensor output U as a function of the velocity v can be described by the following expression:

$$U_{Sensor} = U_0 \cdot \log \left(\frac{I_0/I_n}{1 + \frac{I_0/I_n}{v/v_0}} \right) \tag{4}$$

with U_0, I_0, I_n and v_0 being circuit specific parameters. The results of the measurement are shown in figure 4.

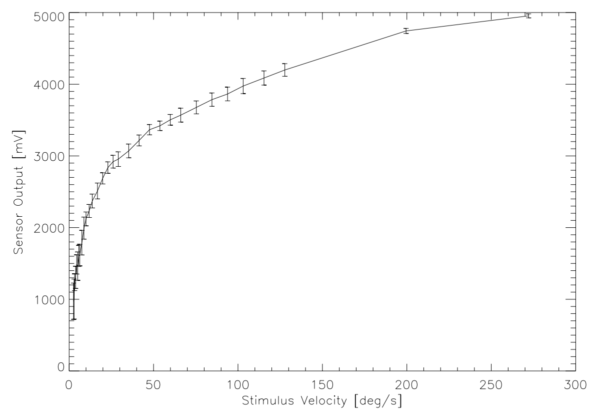

Fig. 4. Sensor response to vertical bar pattern

The results are in good agreement with the theoretically expected curve as described in equation (4) and the measurements by Kramer et al. as is shown in figure 5:

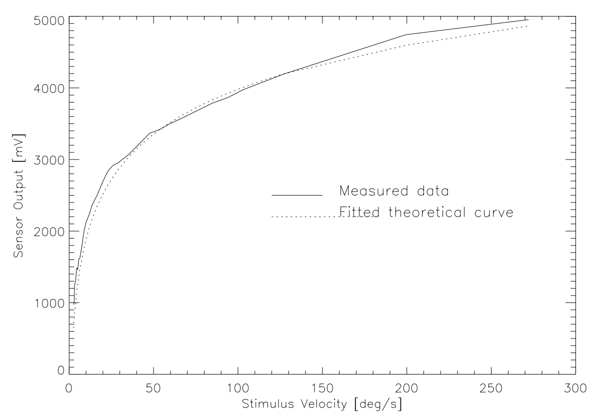

Fig. 5. Measured and theoretical sensor response (vertical bar pattern)

An important result is the reliable behavior of the sensor for rather high rotation speeds of over 200° per second, corresponding to over 2000 image pixels per second or 67 image pixels per frame if a common CCD camera with a wide angle lens is used. If a telephoto lens is used, the number of image pixels per frame gets even higher. In this velocity regime calculation of motion using a correlation method on a typical workstation will be 1 to 2 orders of magnitude slower than the required video rate. Even when optimized methods are used (e.g., [Bor96b] or [Bor96a]), real-time performance is hardly achievable.

So far it has been shown that a rotating sensor is capable of measuring its speed of rotation given a high contrast and simply structured environment. The crucial question is whether the sensor also works reliably in a natural environment. To demonstrate that, we removed the circular wall and used the lab as surrounding environment. There was neither special lighting nor special arrangements to increase contrast or otherwise improve the sensor's performance.

As can be seen in figure 6, the results of this measurement are qualitatively the same as with the artificial bar pattern:

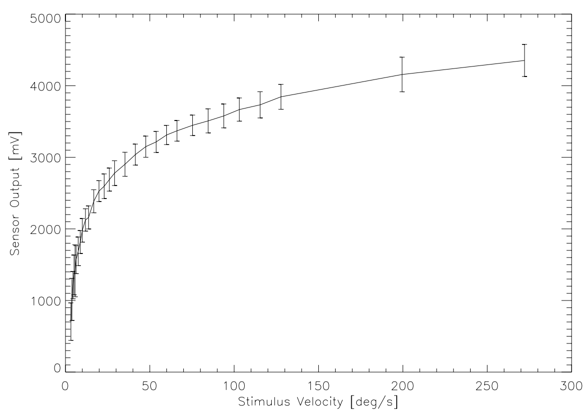

Fig. 6. Sensor response to natural scene (laboratory)

5 Discussion

Due to the good performance of the sensor we claim that it can be used for a purely visual measurement of fast rotation in natural environment. It must be noticed, though, that the sensor's output for such an environment is about 15% lower than in the simple-pattern case. This can be explained by the contrast dependency of the sensor which is shown in figure 7.

As can be seen the sensor output is only contrast dependent for low contrasts. Since the lab not only shows high but also low contrast features, the average output of the sensor was lower than it was with the high contrast bar pattern.

The contrast dependency of the sensor output for low contrast is not a serious problem, though, since the circular sensor shown in figure 2 will provide a confidence measure which is proportional to the contrast. This will allow for compensation of the contrast dependency.

6 Conclusions

A VLSI based system was presented for measuring the rotation speed of a fast rotating platform. The system was able to correctly report the rotation speed

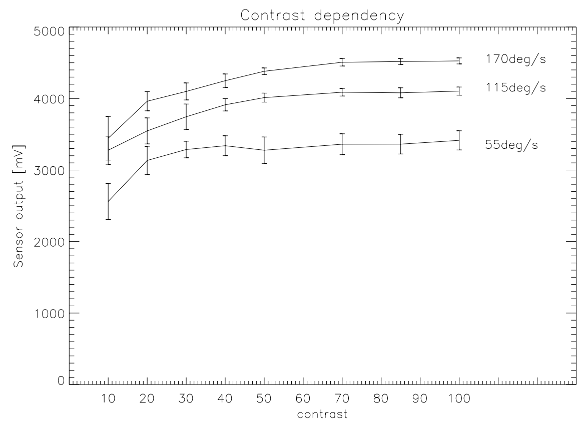

Fig. 7. Contrast dependency for various signal velocities

even in a velocity regime that is significantly above the limit of video-based systems. Due to the used technology, the entire system is built as a single integrated circuit, works in real time and consumes very little power.

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