Autonomous Vehicle Guidance Using Analog VLSI Neuromorphic Sensors

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Abstract. Analog VLSI circuits implementing aspects of biological systems are attractive for the construction of compact low-power autonomous systems. We describe such a system, consisting of a mobile robot equipped with a neuromorphic sensor implementing a one dimensional silicon retina. Specifically, we demonstrate how the real-time visual pre-processing capabilities of the neuromorphic sensor are instrumental in enabling the system to reliably and autonomously track a continuous edge. We present data both from the neuromorphic sensor and from the overall system, performing a line tracking task.

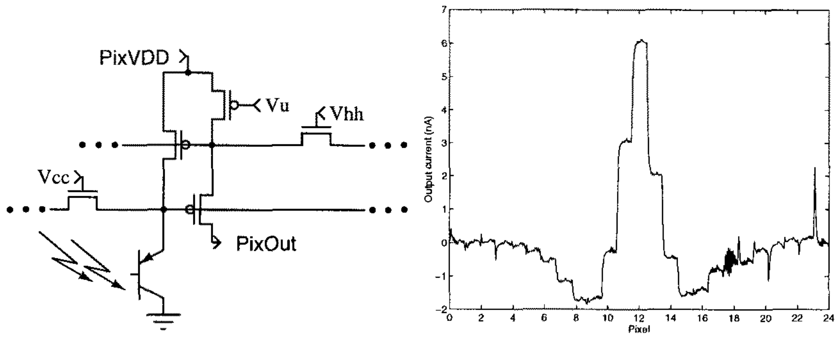
1 Introduction

Real-time autonomous systems such as small robots require dense and power efficient computation. Hardware devices and software algorithms carrying out such computations need to be robust to noise, tolerant to adverse conditions induced by the motion of the system (*e.g.* to jitter and camera calibration problems) and possibly able to adapt to the highly variable properties of the world. Although traditional digital technology provides a fine infrastructure for such systems, it is not suited to the many fast dense computations that occur particularly in sensory and motor processing. For instance, standard CCD cameras will not compensate for local variations in the illumination of a scene. Additional (digital) post processing of images would be needed to extract features relevant for the task at hand. This would increase the power consumption of the system and take up computational resources that could be used more efficiently on other problems. On the other hand, biological systems, constructed around very different principles than the digital systems developed over the last decades, seem to solve effortlessly and efficiently perceptual tasks. For instance, the image that falls on the retina is not transduced to the visual areas as a set of unrelated pixel readings, but is processed locally at each photoreceptor to express neighborhood relationships present in the image. The processing of the image, is tightly coupled to the actual sensing and transduction performed.

By incorporating the principles of biological sensory systems into analog VLSI technology the field of neuromorphic engineering attempts to build the types of devices mentioned above, while trying to gain further insight into the principles of biological computation. Neuromorphic sensors are compact analog VLSI devices that implement models of biological sensory systems [5], [1]. Typically these types of devices contain a variety of circuits used for tasks that range from transducing an input stimulus (such as a luminous or auditory signal) into voltages and currents, to interfacing the analog device itself with other digital or analog devices. Examples of implementations of neuromorphic systems have already proven to be successful in a number of applications ranging from auditory processing to motion computation [10] [6] [4] [7] [8]. In this paper we present a neuromorphic system consisting of a mobile robot equipped with an analog VLSI sensor which implements a one-dimensional retina [3]. This analog low-power device provides the robot with a fast, parallel and low-cost solution for real-time sensory information pre-processing. We designed a simple controller, programmed on the robot's CPU to perform a tracking task, that uses the data processed by the silicon retina. Despite the simplicity of the controller, the system was able to reliably track edges in real-world environments, under variable illumination conditions. This project is a first step towards the design of a fully autonomous vehicle that will safely navigate using only inputs from several of these neuromorphic sensors. Central issues in this study are the ease and reliability of the analog-digital interfacing between the robot's CPU and a neuromorphic sensor, and the robustness of the sensor readings under varying illumination and stimulus conditions.

2 The vision chip

The analog VLSI chip was fabricated using a 2μm CMOS technology and it measures 2.22×2.22sq.mm. It contains a one dimensional array of 25 pixels that implements a model of the outer-plexiform layer of the vertebrate retina, as proposed by Kwabena "Buster" Boahen [3]. The circuit diagram of a single pixel is shown in Fig. 1(a). In the complete array, neighboring pixels are coupled through both excitatory and inhibitory connections. The strength of excitatory and inhibitory connections can be set by the global voltage values V_{hh} and V_{cc} respectively (see Fig. 1(a)). These lateral interactions between pixels produce antagonistic center-surround properties resembling the ones of the neurons present in the very first stages of the vertebrate visual pathway. As a result the overall system performs an operation that effectively corresponds to a convolution with an approximation of a Laplacian of a Gaussian function (see Fig. 1(b)). The voltages V_{hh} and V_{cc} determine the width of the effective convolution kernel, and thus the spatial frequency sensitivity of the sensor. Convolution of an image with a Laplacian of a Gaussian is a common operation used in machine vision to extract edges [2] . This operation, computed in parallel on the silicon retina, typically requires a significant amount of CPU time, if performed using traditional imagers coupled with digital processors (*e.g.* for an array of N pixels and a convolution kernel of size M, the CPU would need to compute N×M floating point multiplications plus N×M shift operations).



(a) (b)

Fig. 1. (a) Circuit diagram of the current-mode outer-plexiform layer model. Phototransistors generate light-induced current at each pixel location. The current is then diffused laterally to neighboring pixels, by the n-type MOS transistors with gate voltages V_{hh} and V_{cc}. (b) Spatial impulse response of the silicon retina. A thin bar was projected onto the retinal plane using an 8mm lens, with a focal length of 1.2. *PixVDD* was set to 3.5V, V_{cc} to 2.48V, V_{hh} to 4.67V and V_u to 2.45V. We implemented off-chip offset compensation by subtracting the *dark-current* outputs from the image outputs.

3 The autonomous vehicle

In these experiments we used the mobile robot *Koala* (K-Team, Lausanne). Koala is 32cm long, 31cm wide and 11cm high. It has a Motorola 68331 processor, 1Mbyte of RAM, and two to three hours of autonomous operation from its battery. An 8mm lens with a 1.2 focal length factor, was mounted directly on the chip socket. The chip, mounted on a wire-wrap board together with an off-chip current sense-amplifier and potentiometers, was attached to the front of Koala with the lens tilted towards ground at an angle of approximately 45^0, in a way to image on the retinal plane the features present on the floor approximately 20cm ahead. The outputs of the retina's pixels were scanned out of the chip by a one dimensional static scanner, clocked by pulses from a digital output port on Koala. The scan synchronization signal, used to determine the position of the first pixel of the array, was read from a digital input port on Koala. The actual analog pixel values were fed into one of Koala's six analog input ports and digitized at 8 bit resolution.

We programmed Koala's CPU to track the strongest edge picked up by the silicon retina. The program was cross compiled for the 68331 CPU on Koala and up-loaded over the serial link. Once it was resident in Koala's RAM the serial connection was removed and the robot operated autonomously. The software implements a controller which determines the rotational motion component to be added to a default translational motion term (see Fig. 2). The controller is very

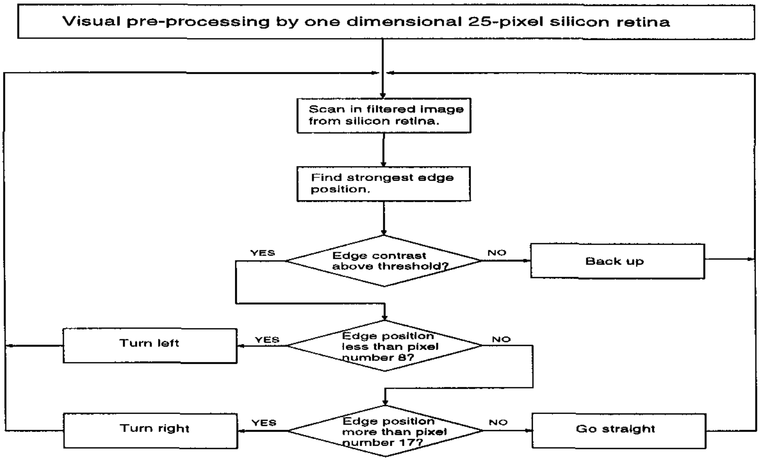


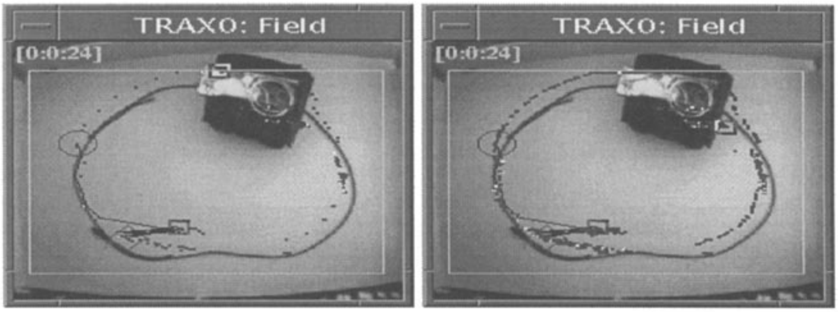
Fig. 2. The simple tracking controller structure implemented on Koala, which gives a good performance in conjunction with the "cheap" but sophisticated analog VLSI sensory processor.

simple. It contains no means to correct for overshoots, no sophisticated search strategy in case no edge is detected, nor any temporal filtering for estimating future possible edge positions, based on previous data. This implies that, in order for the robot to follow a continuous edge, the visual pre-processing implemented by the retina must be very robust. Any failures of the retina to detect an edge in its small field of view could lead the system to an unrecoverable error.

The arena in which we evaluated Koala's tracking performance, measured 1.1×1.55 square meters (see Fig. 3). The stimulus, a black power cable, was taped to the floor of the arena. The length of the cable, was 2.4 meters. Multiple experiments were performed under varying conditions of natural illumination, and different motion parameters. Koala was logged continuously using a custom tracking system, TRAX [9], that received input from a ceiling mounted CCD camera.

Subsequent points in the trajectory of the tracked object are displayed by TRAX only when they are more than 10 pixels apart (see Fig. 3(a)). In this particular experiment the 10 pixel gap translates to spatial distances of 7cm. This property allows a direct evaluation of the repeatability of the behavior displayed by a monitored object. Closely grouped dots indicate the re-visitation of nearby positions over time.

Figure 3 shows a representative trajectory. Figure 3(a) displays the first 5 meters of traveled distance, while Figure 3(b) shows the full trajectory after approximately 100 meters. An interesting aspect of the trajectory, which is made up of multiple cycles along the cable, is its repeatability over time. This is most noticeable in the left part of the depicted trajectory. The small deviations from the ideal trajectory are partially artifacts of the tracking system mainly due to the sensitivity to fluctuations in the illumination conditions of the CCD camera.



(a) (b)

Fig. 3. Trajectories of the robot measured by TRAX. The continuous smooth line is a power cable taped to the floor. The dotted line indicates the sequence of robot positions as it tracks the line edges. Figure (a) represents the trajectory as recorded in the first laps, whereas figure (b) shows the full trajectory after a total of forty laps.

This erroneous input of our tracking system illustrates an important difference between the two types of sensors used in this experiment: a neuromorphic retina and a CCD camera. Neuromorphic sensors have significant advantages in real-world applications, where robustness to variations in illumination conditions and varying task demands is essential. The practically invariant trajectory generated by the robot over time is remarkable given that the visual field of the retina is very small, there are strong fluctuations in the local illumination conditions in the arena (see Fig. 3) and the controller is very brittle.

4 Discussion

In this paper we described the use of a neuromorphic sensor for pre-processing of sensory data, applied to the control of a mobile robotic. Our results indicate that the use of neuromorphic sensors is technically possible and practically useful. The analog VLSI retina provided a robust input signal for a simple line tracking system implemented on an autonomous robot. We intend now to integrate 2D retinae and motion sensors in the control of visually guided behavior on autonomous mobile robots.

Acknowledgments

We would like to thanks Rodney Douglas for his constructive comments and support, and Francesco Mondada and Edo Franzi for their help with Koala. This work was inspired by the 1996 Telluride Workshop on Neuromorphic Engineering (funded by the U.S. NSF and the Gatsby Foundation) and was supported by the Swiss National Science Foundation. Fabrication of the integrated circuits was provided by MOSIS.

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