A PUSH-PULL MODEL OF ORIENTATION-SELECTIVITY IN A HYBRID VLSI SYSTEM OF SPIKING NEURONS

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Summary

We describe the use of a programmable, rewireable, multi-chip aVLSI neuronal system in creating orientation-selective spiking neurons with various receptive fields using a feedforward model. The multi-chip system consists of a silicon retina, an asynchronous router board, and a transceiver multi-neuron chip. The three modules communicate using the asynchronous arbitered address-event representation (AER) protocol. This protocol uses asynchronous digital pulses, similar to spikes in a neuronal system. The circuit on the multi-neuron chip approximates a cortical microcircuit. The receptive fields of the neurons are configured by the virtual connections of selected sets of pixels on the silicon retina. These connections are effected through the programmed look-up table on the field programmable gate-array (FPGA) chip on the router board: This table sets the destination addresses for the incoming retina addresses.

We used the multi-chip spike-based system to synthesize orientation-tuned cortical-like neurons with different receptive fields. In particular, we used this system to explore the neuron's response for two feedforward models. In the first model, the retinal inputs drive the neuron only through excitatory synapses, and in the second model, the retinal inputs drive the neuron through both excitatory and inhibitory synapses similar to a push-pull model [Hubel and Wiesel, 1962]. We found that a neuron whose orientation-selectivity comes from a push-pull model arrangement of the retinal inputs is more robust to the variation in the timing of the input spikes and responds over a wider range of stimulus speeds than a neuron whose receptive field is generated purely through an excitatory feedforward model.

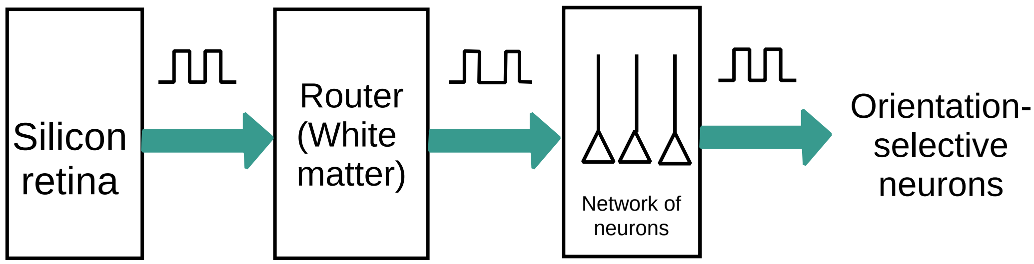


Figure 1: Block diagram of a multi-chip system in which virtual connections from a set of neurons on a silicon retina onto another set of neurons on a transceiver chip are described using the router module. The router communicates with the multi-neuron chip if the spike address from the retina falls within the lookup table programmed on this module.

Introduction

Multi-chip VLSI neuronal systems are recently developed to mitigate the simulation time of neuronal networks. These systems support the study of spike-based cortical processing models. The connectivity between neurons on different chips and between neurons on the same chip are reconfigurable. The receptive fields of neurons are effected by appropriate mapping of the spikes from source neurons to target neurons. The neurons are integrate-and-fire types. They spike whenever the summation of the incoming EPSPs exceed a threshold. A significant advantage of these hardware simulation systems is their real-time property; the simulation time of these systems does not increase with the size of the network.

In this work, we used a multi-chip system consisting of a silicon retina, a router module, and a multi-neuron chip, to create orientation-selective neurons using two feedforward models. We used this system to evaluate the responses of these neurons in a physical system where mismatches and noise are always present. The first model is a purely feedforward excitatory model and the second model is a push-pull model [Hubel and Wiesel, 1962]. We compare the responses of these two types of neurons to a range of stimulus speeds. A model that is robust to variations in input spike timings which naturally occur in a real physical system and has a response over a wide range of speeds is more appropriate for describing the appearance of orientation-selectivity in the simple cells in the visual cortex. We find that the neuron implemented using the push-pull model is more robust than the neuron implemented using a pure excitatory model.

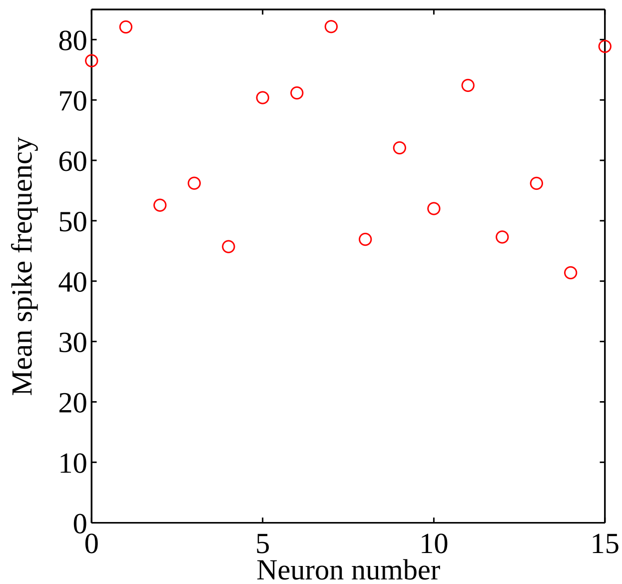


Figure 2: Distribution of the mean spike rates of the 16 neurons on the multi-neuron chip for a regular input spike train of 50 Hz. Due to circuit mismatches, the steady-state spike rate varies among the neurons.

Methods

The system (Fig. 1) consists of a 16 $\times$ 16 silicon ON/OFF retina, an asynchronous router with a field programmable gate array (FPGA) chip, and a transceiver chip comprising a ring of 16 excitatory integrate-and-fire neurons and a global inhibitory neuron. All three modules communicate using the arbitered address event representation (AER) protocol [Lazzaro et al., 1993, Mahowald, 1994, Boahen, 2000]. The communication channel signals consist of the address bits of the active pixel/neuron on the sender chip and the handshaking signals. The handshaking signals ensure that the receiver loads in the correct address bits from the sender. The router and the multi-neuron chip are both transceivers: they can both receive events and send events. In prior work, we discussed a similar orientation-selective system where the mapper module was a microcontroller and the receptive fields of the neurons were implemented using a purely excitatory model [Liu et al., 2001]. The communication between all modules including the router board in the system described in this work is totally asynchronous.

The retina with an on-chip arbiter acts only as a sender. Each pixel comprises an adaptive photoreceptor with a rectifying temporal differentiator [Kramer, 2001] in its feedback loop. Positive temporal irradiance transients (dark-to-bright or ON transitions) and negative irradiance transients (bright-to-dark or OFF transitions) appear at two different outputs of the pixel. The pixels are arranged on a rectangular grid and are not spatially coupled. The position of a pixel along a row is encoded with a 4-bit column address (X address) and its position along a column with a 4-bit row address (Y address). The outputs are coded in the form of asynchronous binary pulses, which also act as the request signals to the AER communication interface. We assume that the spike outputs from the retina approximate the ON/OFF outputs of the lateral geniculate nucleus (LGN) neurons. The retina can be set in two modes: the non-bursting mode and the bursting mode. In the non-bursting mode, the pixel responds with a single spike to the onset of a stimulus regardless of the stimulus contrast. In the bursting mode, the pixel responds with multiple spikes to the stimulus contrast. The number of spikes in response to a certain contrast can be set by an external parameter.

The multi-neuron chip is a transceiver. It consists of an array of integrate-fire-neurons with simple current-integrating synapses. The chip receives AER events which stimulate one of the exitatory or inhibitory synapses on the neurons. The neurons also transmit their addresses off chip. The excitatory neurons on the chip excite a global inhibitory neuron which in return inhibits the excitatory neurons. The neuron has external adjustable global parameters that control its threshold voltage, the pulse width of its output spike, its refractory period, and its time constant. The efficacy and temporal dynamics of each synapse can be controlled by two global parameters.

The neurons on this chip have an inherent mismatch which arises from the synapse and soma circuitry within each neuron. This mismatch leads to a variance in the output firing rates of the neurons even when the neurons are stimulated by the same presynaptic frequency (see Fig. 2). The membrane potentials of the neurons can be monitored by an on-chip scanner and the output spikes of the neurons can be monitored by the tranceiver chip's AER output.

The receptive fields of the neurons on the transceiver chip are created by configuring the connections from a subset of the source pixels on the retina using a lookup table which is programmed on the FPGA chip on the asynchronous router board [Häfliger, 2001]. Through this lookup table, an event is transmitted to the appropriate transceiver multi-neuron chip if the incoming retinal spike lies within one or more of the receptive fields (RFs) of the neurons on the transceiver. The latency of the board in transmitting a retinal address is only about 100 ns. As a result, the statistics of the ISI distribution are not distorted by the presence of the board. At present,

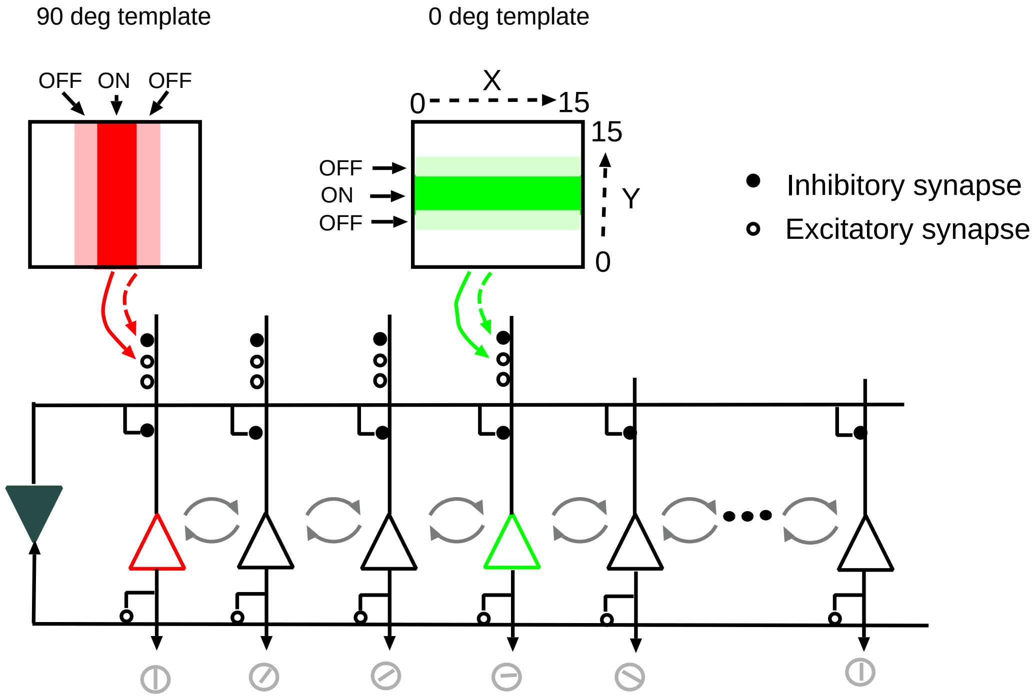


Figure 3: Spikes from a selected set of neurons within the different regions on the retina were mapped onto the corresponding orientation-selective neurons on the transceiver chip. The hollow triangles mark the somas of the excitatory neurons and the solid triangle on the left marks the soma of the global inhibitory neuron. Only two neurons, mapped for orthogonal orientations, were used in this experiment. The mapping was implemented in accordance to the push-pull model. The receptive field of each neuron consists of a center ON region and two flanking OFF regions which excite the neuron (solid line). The complementary input type (center OFF region and two flanking ON regions) for each region inhibits the neuron (dashed line).

the cycle time of the board is limited by the speed of the transceiver chip during the handshaking process.

Results

Only two neurons on the transceiver chip were mapped in this experiment as shown in Fig. 3. These neurons had orthogonal preferred orientations. The local excitatory coupling between the neurons was disabled and the global inhibition was also disabled.

The neurons charge up to threshold through the summation of the incoming EPSPs: If the ISIs of the incoming spikes are too large, the neuron will not spike. The minimum ISI value needed for the neuron to reach threshold depends on the time constant of the soma which is set a leak transistor in the neuron's circuit. The size and aspect ratio of the neuron's receptive field and the weight of the synapse also determine the responses of the neurons. The synaptic weight determines the number of EPSPs needed to drive the neuron above threshold.

The receptive field of each neuron using the first model consists of only a center ON excitatory region of size $3^o \times 1.8^o$ (an area of 5 by 3 pixels on the retina array) while the receptive field using the second model consists of a center ON excitatory region ($2.4^o \times 1.2^o$ or an area of 4 by 2 pixels on the retina); and two flanking OFF excitatory regions ($2.4^o \times 0.6^o$ each or an area of 4 by 1 pixels on the retina) as shown in Fig. 3. The complementary input type (center OFF and flanking ON) in each region inhibits the neuron.

A rotating drum with a black and white strip was placed in front of the retina. The field of view of the chip is approximately 9.5^o. The retina was set in the bursting mode; the refractory period of the neuron in the retinal pixel was around 100 μs. The spike addresses and spike times from the retina in response to an image speed of 7.9 mm/s (or 89 pixels/s) from the strip on the rotating drum were recorded using a logic analyzer.

Data was collected from the two neurons on the multi-neuron chip for different orientations of the stimulus spaced at 30 deg intervals. The stimulus was presented approximately 500–1000 times to the retina. The parameters of the different chips were tuned separately for the two models so as to obtain the most optimal response from the neurons under the different experimental conditions. In the case of the excitatory model, we found the response of the neuron was quite sensitive to the parameter settings of the neuron and we had to set the retina for the nonbursting mode so that events are sent only once from the retina when a pixel sees an edge. In contrast, the neuron implemented using the push-pull model was less sensitive to parameter settings and we could set the retina for either the bursting or non-bursting mode and there was a distinction in the output rates of the neuron for different oriented stimuli.

The response of the neuron mapped using the push-pull model to an OFF edge in its preferred orientation passing through its receptive field is shown in Fig. 4(a). The top trace shows the membrane potential of the neuron and the bottom trace shows the groups of input spikes to the multi-neuron chip from the router board during this period. The four groups correspond to the input spikes from the four rows of the retina comprising

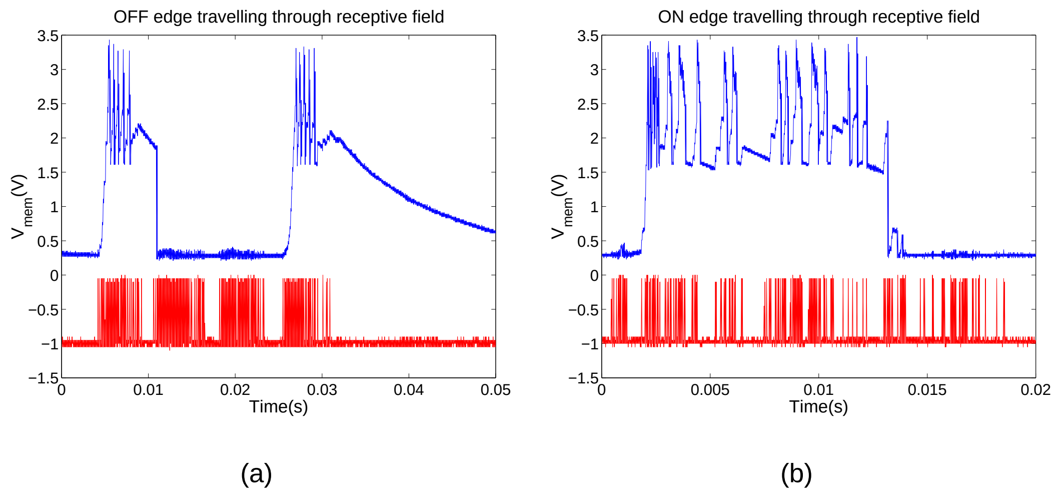
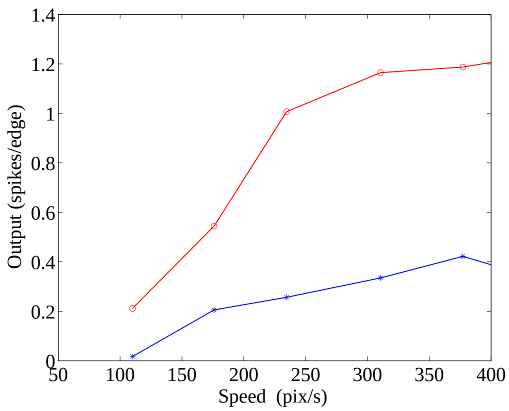
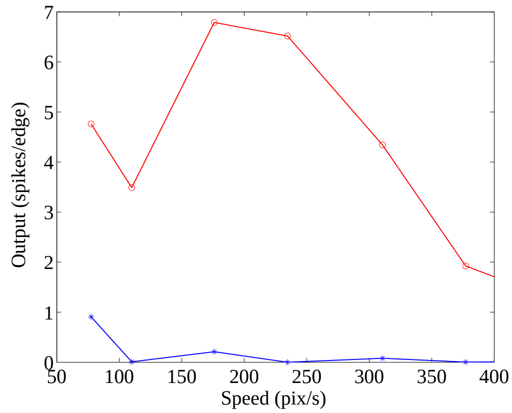


Figure 4: The response of the neuron to an OFF edge (a) and to an ON edge (b) of its preferred orientation moving through its receptive field (RF). The bottom trace in each figure shows the input spikes to the multi-neuron chip from the router module when the edge moved across the retina array. The four groups of spikes correspond to the spike outputs from the four rows of the retina that comprise the neuron's RF. The top trace shows the membrane potential of the neuron during this period. In (a), the neuron received excitatory input spikes when the OFF edge moved through one of the flanking regions of the RF. The sharp transitions riding on top of the neuron's output are spikes that occured when the membrane voltage exceeded the neuron's threshold. When the edge moved into the center of the RF, the neuron was quickly inhibited as indicated by the sharp drop of the membrane voltage during this time. The neuron again built up to threshold when the OFF edge entered the second excitatory region of the RF. The membrane voltage discharges once the edge leaves the receptive field. The time constant of the neuron is about 10ms. In (b) we only show the response of the neuron when an ON edge travelled through the center excitatory region of the RF.

neuron's receptive field. The neuron responded when the OFF edge travelled through the first excitatory subregion. The sharp transitions on top of the neuron's response are the output spikes. In between input spikes, the membrane of the neuron discharged at a time constant of around 10 ms. When the edge travelled through the center subregion, the neuron was quickly inhibited as evidenced by the sharp drop of the membrane potential at the start of the second group of input spikes on the bottom trace.



(a)



(b)

Figure 5: Speed tuning curves of a neuron mapped using the excitatory model (a) and the push-pull model (b). The receptive field sizes are described in the text. The two curves in each figure are results from the neuron when the stimulus was at the preferred orientation and at the orthogonal non-preferred orientation. The spike rate was computed as the average number of spikes from the neuron when the edge moved across the entire retina array.

The neuron built up to threshold again when the edge travelled through the second excitatory subregion of its receptive field. Figure 4(b) shows the same curves in the presence of an ON edge of the preferred orientation travelling through only the center subregion of its receptive field.

In the next experiment, we presented the stimulus at different speeds and recorded the firing rates of the neurons when implemented with the two models. The spike rate was computed as the average number of spikes from the neuron when the edge moved across the entire retina array. The speed tuning curves of a neuron implemented using the excitatory model are plotted in Fig. 5(a) and implemented using the push-pull model is shown in Fig. 5(b). The curves show that the difference in the spike rates recorded in response to the preferred and non-preferred orientations is larger for the neuron implemented using the push-pull model.

Conclusion

We used a programmable multi-chip VLSI system to explore spike-based orientation-selective models. This system has advantages over computer neuronal models in that it is real-time and the computational time does not scale with the size of the neuronal network. The spiking neurons on the multi-neuron chip can be configured for different receptive fields. In this work, we showed that a neuron mapped using a push-pull model responded over a large range of stimulus speeds when compared to a neuron mapped using a feedforward excitatory model. The response of the push-pull neuron is also more robust to the variations of input spike timings that occur in a natural physical system.

Acknowledgments

We acknowledge J. Kramer for the silicon retina, G. Indiveri and T. Horiuchi for the original transceiver design, P. Hafliger and T. S. Lande for the map programmer code and the router board, David Lawrence for the software driver development, and K. Martin for multiple discussions in this work. This work was supported in part by the Swiss National Foundation Research SPP grant.

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