THE CONTINUOUS RETINA: IMAGE PROCESSING WITH A SINGLE-SENSOR ARTIFICIAL NEURAL FIELD NETWORK

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Abstract

Silicon retinas are typically implemented with multiple photosensors. Recent work with VLSI extended analog computers has led to a single-photosensor retina. It is called a continuous retina because the image focused on it generates a current gradient within the sensor, as opposed to independent currents in multiple sensors. The current gradient is discretized into an analog output vector, then classified by a trainable on-chip artificial neural field network. The continuous retina is compact. A VLSI implementation that recognizes several letters fits onto one MOSIS "TinyChip".

1. Introduction

It is natural for biologically-inspired devices to model cellular structures. Silicon retinas are therefore typically implemented with multiple sensors, and often contain additional processing elements within the sensor array to model early vision tasks such as edge detection, motion detection, or corner recognition. All of the silicon retinas known to the author take this approach [Harris/Koch/Luo/Wyatt89, Hutchinson/Koch/Luo/Mead88, Mead89, Mills92, Mills93, Sheu/Choi95, Van der Spiegel89].

The continuous retina presented in this paper represents a different approach. It is inspired by the observation that neural systems can be modeled by real-valued continuous fields [MacLennan90]. MacLennan calls such abstract systems *field computers.* Biological examples of field computers such as the ocular dominance stripes in the visual cortex support the model [Hubel/Weisel62]. MacLennan did not implement a field computer, but his work did inspire the design of artificial neural field networks [Mills95a].

Artificial neural field networks (ANFNs) model the behavior of a network of fields of neurons. A neural field is an aggregate of neurons and their external inputs whose output can be defined by a single function. The neural field function is the composition of the pair of functions F and L that compute the weighting, summing, and activation functions of each neuron in the field. F is non-adjustable. It computes the sum of the synaptic inputs into and within the field weighted by locality of the input; the weights are not adjustable. L is adjustable, and computes a variable transfer function for the field. F separates non-linearly-separable inputs, while L maps the output of F to some desired encoding. ANFNs are trained by selecting the best L for each field.

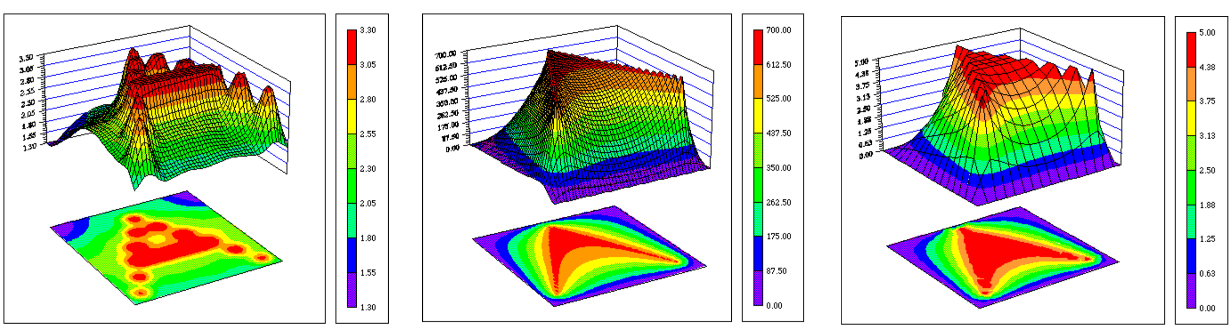
Viewed as an ANFN, the continuous retina implements F as a single-pixel sensor, and L as a collection of programmable function generators whose output encodes the identity of the image recognized. When an image is focused on the continuous retina it generates a current gradient within the sensor — a field — as opposed to independent currents in multiple sensors. The current gradient is discretized into an analog output vector, then classified by the programmable function generators. The early vision tasks explicitly performed by multiple-sensor retinas are subsumed by the field computation of the ANFN.

The continuous retina and other ANFNs are implemented as extended analog computers (EAC) [Rubel93]. VLSI EACs are composed of conductive sheets surrounded by multiple Lukasiewicz logic arrays (LLAs) [Mills95b]. LLAs are arrays of current mirrors that implement Lukasiewicz implication, A ⊃ B, algebraically equivalent to *min(1, 1-A+B)* [Mills/Beavers/Daffinger90, Mills92]. The topology of the conductive sheet, the material from which it is constructed, and the boundary-value LLA functions determine the computation that the EAC performs. EACs are Turing-complete. They are theoretically capable of solving more complex problems than conductive sheets or resistive meshes alone, which have long been known to solve the partial differential equations that describe field problems [Kirchhoff45, Karplus58]. For example, an EAC can control a quadropole electromagnet in a cyclotron beam line by solving the boundary-value problem that describes the particle beam and using the solution to generate a control signal [Mills95c].

The continuous retina is compact because the EAC's conductive sheet doubles as the ANFN's F function, reducing explicit inter-sensor wiring to zero. The L function is implemented as four LLAs with an analog computation path that does not require ADCs and DACs. A VLSI implementation fits onto a MOSIS "TinyChip", and can recognize several block letters.

2. Simulation

The major question about the design of the continuous retina concerned the conductive sheet sensor: would sufficiently distinct current gradients result? Three simulation approaches were used. A foam conductive sheet was built that generated surfaces from attached electrodes simulating vector characters focused on the conductive sheet. The simulated photocurrent gradient was measured on a 13x14 grid (Figure 1a). MatLab was used to simulate a square conductive sheet modeled by Poisson's equation with the diffusion constant set to the permittivity of silicon. (PISCES uses a similar approach [Dutton/Yu93]. PISCES can also handle implantation discontinuities used to form MOSFET and BiCMOS device, but these are not a factor in conductive sheet design.) The sheet was discretized for output onto a 50x50-element square mesh (Figure 1b). A preprocessor for SPICE [Almeter95] was used to generate a 16x16 finite-element mesh of resistors, with electrodes modeled as 1 ohm resistors (Figure 1c).



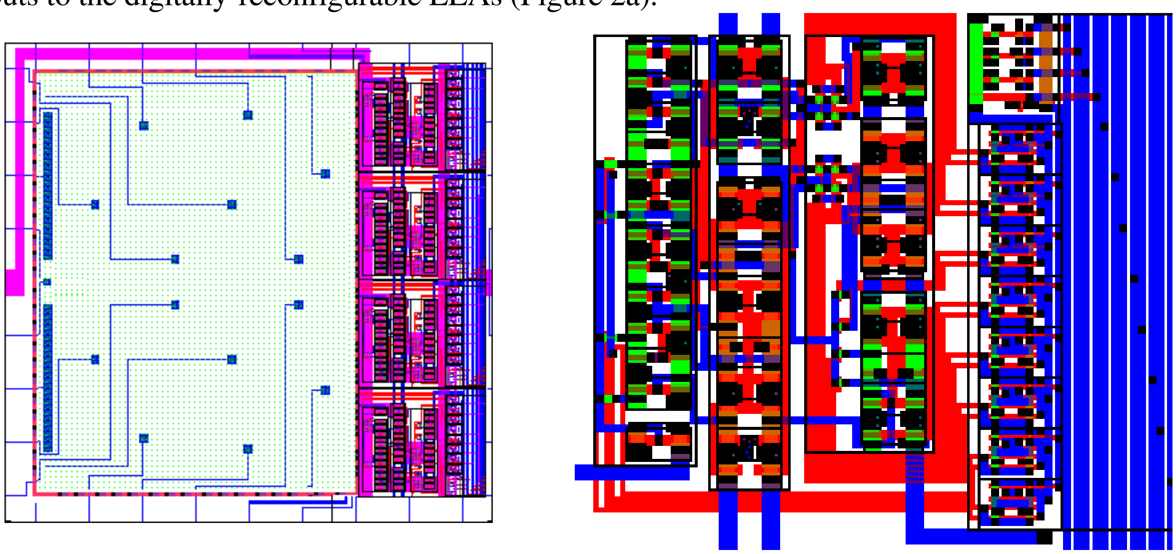
(a) (b) (c)

Figure 1.

No single simulation modeled the anticipated behavior of the conductive sheet correctly. All simulations resulted in discontinuities in the output: the foam and MatLab simulations because the output was discretized; the SPICE simulation because the inputs were discretized on the resistive mesh. The MatLab and SPICE simulations did not indicate the probable resolving power of the sheet because ideal infinitely-thin 2-dimensional sheets were used in the model. The current flow into the substrate was ignored as a result (this would not have been a problem with PISCES). The current flow was modeled by the foam because the foam has substantial thickness (5mm). However the foam simulation introduced error due to its anisotropicity: current flowed unevenly as well as more easily along the x-axis than the y-axis. This deformed the current gradient laterally, a problem that did not occur in the MatLab and SPICE simulations. However, the combination of simulations was considered sufficiently accurate to submit the design for fabrication. PISCES is being obtained for future work, and to compare to the foam simulation.

3. VLSI implementation

The prototype continuous retina was laid out as a MOSIS "TinyChip" with outputs from the conductive sheet sensor available at separate pins where they are wire-summed and redirected as inputs to the digitally-reconfigurable LLAs (Figure 2a).



(a) (b)

Figure 2.

The conductive sheet sensor is enclosed in a guard ring, and implements a lateral diode (Figure 2a, large area at left). The diode is reverse-biased during operation to prevent charge carriers from leaking away from the output probes. An image focused on the conductive sheet induces a current gradient by the photo-electric effect. The conductive sheet sensor is the largest and most robust part of the retina. Defects that would cause a pixel sensor to fail only introduce a slight inhomogeneity into the sheet. Output probes are wire-summed to sample the current, which is used as an input to four LLAs (Figure 2a, vertical array on the right). If a probe fails, its neighbors can still be used to generate an approximate value. The reconfigurable LLA (Figure 2b) uses digitally-programmable multiplexed inputs and outputs to obtain 256 analog functions. 27 of these are *basis functions* that form a piecewise-linear covering of the continuous [0,1] range and domain dissected by {0, .5, 1} (Figure 3).

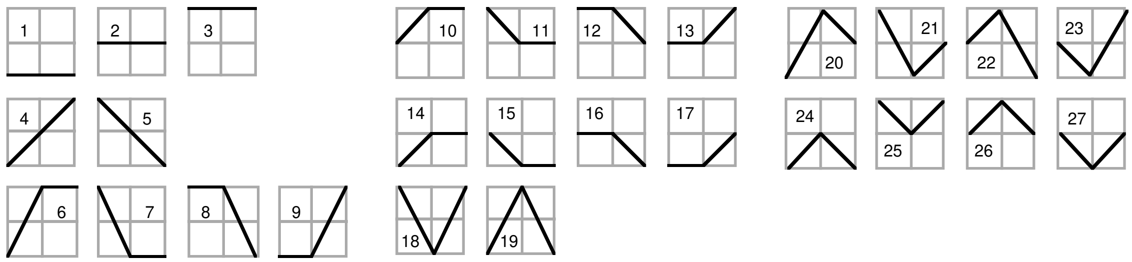


Figure 3.

The retina classifies its input in about one microsecond, determined by the time needed to generate the photocurrent and by the slew rate of the LLAs [Biswas94]. The conductive sheet stabilizes in time proportional to its corner-to-corner diagonal's length. For example, the RC time constant for a conductive sheet sensor composed of n-well with a uniform sheet resistance of $2k\Omega/\mu^2$ and sheet capacitance of 500×10^{-18} farads/μ^2 is 1×10^{-12} seconds, or 1 picosecond/μ^2. For a sheet $1cm^2$ this leads to the estimate that it will stabilize in 14 nanoseconds [Sze81, Weste/Eshraghian93].

A disadvantage of the continuous retina is the problem of sensor saturation: a bright image will generate a current gradient that loses distinguishable features. Experiments with the conductive foam suggest that the contrast of the image can be enhanced by manipulating the substrate voltage. This will be tested when the prototype retina is received from MOSIS.

4. A simple character recognizer

The continuous retina can be operated as a trainable character recognizer, a task often performed by neural networks [Hertz/Krogh/Palmer91, Sheu/Choi95]. Simulation of a simple recognizer that distingishes between "A" and "T" illustrates how the retina is trained using the 27 basis functions. A binary encoding for the characters is chosen, with "A" indicated by 111 and "T" by 000 (if a ternary encoding were chosen it would be barely possible to classify all 26 characters of the alphabet, but in this example a value other than 0 or 1 indicates uncertainty in the classification). The L functions are initially set to produce a 1 for every input to the retina. Presenting an "A" to the retina does not generate an error, so no adjustment of the L functions is possible (Figure 4).

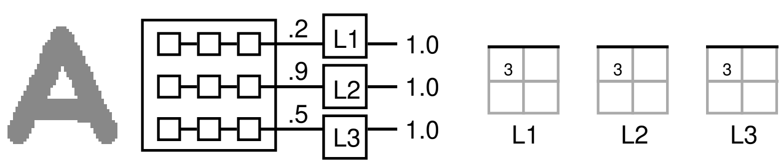


Figure 4.

When the "T" is presented, an error results, which can be used with the desired output and the values input to the LLAs to determine the new L functions. A simple rule for choosing L functions is to minimize the error for the current presentation and the most recent but different character presented. Following this rule, the new L functions are shown in Figure 5.

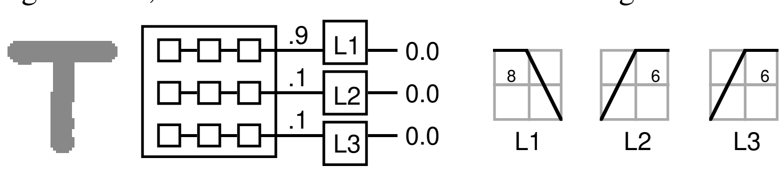


Figure 5.

Presenting "A" again to determine if the retina is trained indicates that this choice of function settings is acceptable (Figure 6).

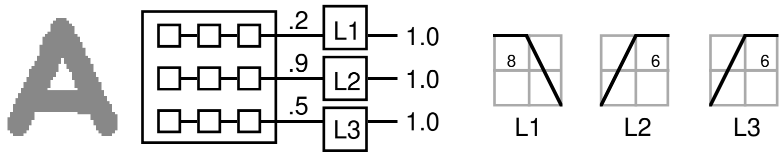


Figure 6.

Finally, the ability of the retina to classify characters as either "A", "T", or similar to one or the other is tested with four images: a scrawled "A", an "H", a "T" with a circular patch removed, and an "F" (Figure 7).

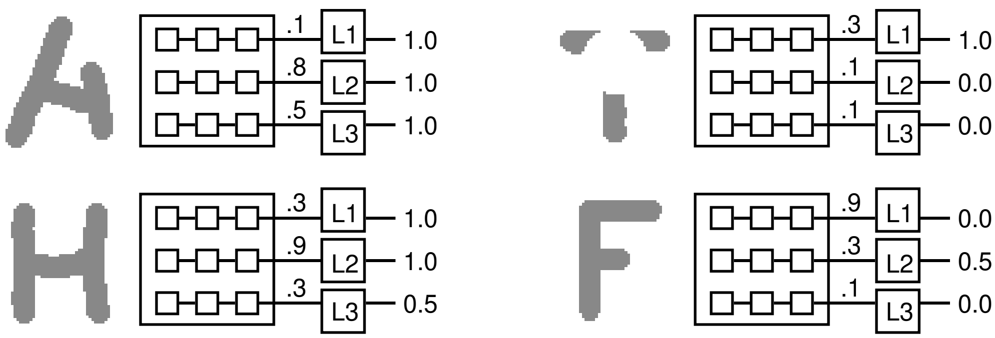


Figure 7.

The retina simulation correctly matches the scrawled "A" and classifies the "H" as being similar to an "A". The broken "T" is correctly matched, while the "F" is classified as being similar to a "T". The recognizer is robust because of the continuity in the induced current gradient and the piecewise-linear L function units. The conductive sheet is inherently capable of smoothing discontinuities in the image. These properties also allow the recognizer to be somewhat tolerant of small scale, rotation and translation variation in the image.

5. Conclusions

The design and VLSI implementation of a single-sensor continuous retina based on the field computer model of neural computation was described. The continuous retina was submitted to MOSIS for fabrication after simulation by both digital and analog computers. The use of the continuous retina as a simple character recognizer was illustrated, and its ability to generalize was explained in terms of the continuity of the conductive sheet sensor and the continuous-valued Lukasiewicz logic arrays used as L function generators.

Future work includes testing the prototype devices, designing more complex recognizers, and implementing a distributed sensor/controller network with continuous retinas on the small hexapod robot, Stiquito [Mills93].

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