Spike-Based Sensing and Processing

AT THE COMPUTATIONAL NEUROENGINEERING LAB AT THE UNIVERSITY OF FLORIDA

I. INTRODUCTION

Dr. John G. Harris co-directs the Computational NeuralEngineering Lab (CNEL) at the University of Florida, together with its founder: Dr. Jose C. Principe. CNEL seeks to advance the theory and applications of adaptive systems using mathematics and anthropomorphic principles. This work is highly multidisciplinary and of broad impact since it is geared to provide new engineering design principles. Analogies from biology are expressed in appropriate mathematical frameworks and implemented in digital algorithms or directly in analog VLSI chips. Since its inception in 1992, the CNEL has created an international reputation in the areas of adaptive filtering theory, artificial neural networks, nonlinear dynamics, neuromorphic engineering, and more recently in brain machine interfaces and information theoretic learning.

Fig. 1. PhD students Vishnu Ravinthula, Dazhi Wei and Xiaoxiang Gong with Dr. Harris.

Within the CNEL Lab, Dr. Harris and his students are engineering sensors and signal processing systems that use biologically-inspired algorithms and custom analog VLSI circuits. There are many aspects of the brain that are desirable to emulate in engineering systems in the long term, including the following notable performance metrics:

1. **Incredible fault tolerance:** the brain loses an average of 10,000 neurons per day without requiring any sort of explicit reconfiguration or rewiring.
2. **Ultra-low power consumption:** The brain consumes an average of 12 Watts, much less than a typical Pentium computer performing much less computation.
3. **Phenomenal performance:** The best man-made engineered solutions pale in comparison to human performance in common sensory processing tasks such as the recognition of faces or speech.

Unfortunately, it is not well understood how the brain achieves its amazing performance but a more immediate advantage of bio-inspired computation is currently being expoited in the CNEL lab: spiking representations. The brain represents signals using the timing of discrete spikes (or pulses) which is a hybrid of traditional analog and digital computation. The pulses are digital in that the amplitude and width of the pulse do not contain information but the timing of the event is asynchronous, and therefore analog. As humans have learned through the years with such systems as digital cellular phones and digital TV, it is much more efficient to transmit digital signals than to transmit continuous analog voltages due to the improved noise immunity and less cross talk susceptibility. The resulting spike-based engineering systems enjoy reduced power consumption and enhanced dynamic range.

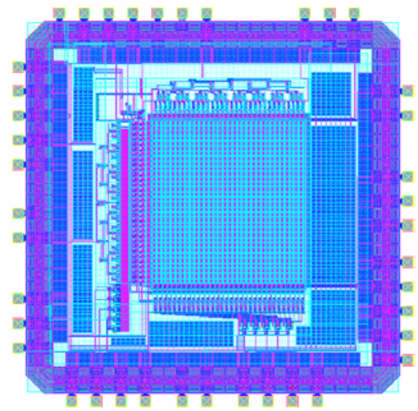

Fig. 2. Experimental 32x32 pixel time-to-first-spike imager.

Through the electronics revolution over the past decades, CMOS process technology is shrinking the usable voltage swing, wreaking havoc on traditional analog circuit design. However, the faster "digital" transistors are better able to process timing signals leading researchers to consider analog computation more similar to that of the brain. This trend will likely continue with nanotechnology since even smaller voltage ranges and even faster devices are promised. Of course, CMOS processes are primarily scaling in favor of faster and faster digital devices, however power consumption is beginning to limit how far these digital circuits can scale.

II. SENSORS

Together with his students, Dr. Harris is developing novel VLSI sensors using this pulse-based methodology. A sensor can typically be designed with a wider dynamic range when time is used to encode the measured signal instead of a voltage, as is the case for typical engineering systems. Graduate students Xiaochuan Guo and Xin Qi have developed a novel time-to-first spike imager using this strategy (see Figure 2).

Fig. 3. PhD students Xin Qi and Harpreet Narula are developing novel spike-based sensors.

Conventional CMOS imagers must choose a single integration time for each pixel which limits the dynamic range to 60-70 dB. On the other hand, each pixel in the time-to-first-spike imager outputs a single spike at a time inversely proportional to pixel intensity. Each pixel therefore chooses a suitable integration time resulting in a greatly enhanced dynamic range of 140dB.

Harpreet Narula has designed a low-power, spike-based potentiostat that can measure currents as low as 1pA. Potentiostats are used to measure electrochemical activity (as a current) for such applications as blood analyzers, food control and glucose sensors.

Du Chen is designing a spike-based neuro-amplifier suitable for implantation. Typical extracellular neural signals have amplitudes of 10-100uV with DC offsets ranging up to 200mV and frequencies ranging from below 1Hz up to 6KHz. A low-noise amplifier was designed to provide a gain of 40dB before translating the output to a series of pulses for efficient transmission.

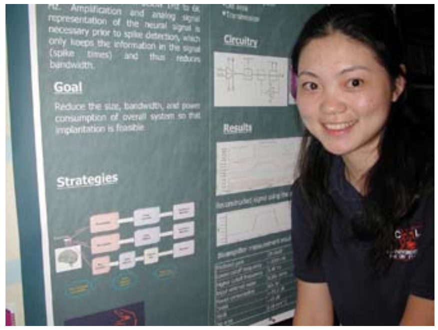

Fig. 5. PhD Student Du Chen is developing spike-based bioamplifiers suitable for implantation.

III. Spike-Based Processing

Rather than convert the spike outputs from the sensors into an analog voltage or a digital signal, the sensor outputs can be processed directly in the spike domain. Time-based signal representations have been in use for many years, including such standard techniques as pulse-width modulation and sigma-delta converters but temporal codes are becoming more and more common with the rising popularity of such techniques as class D amplifiers, spike-based sensors and even ultra-wideband (UWB) signal transmission. However, these temporal codes are typically used as temporary representations and computation is only performed after translation to a traditional analog or digital form.

Xiaoxiang Gong is developing a novel spike-based adaptive filter that processes spike signals as the input and desired signals. Much like traditional adaptive filters, this new class of adaptive filter has applications in areas such as system identification, signal prediction, noise cancellation and channel equalization.

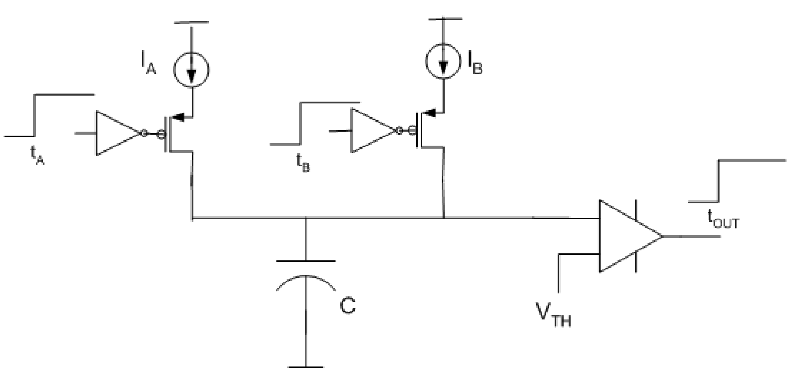

Fig. 4. An arithmetic circuit using the timing of step functions.

Vishnu Ravinthula has developed time-based arithmetic circuits that can perform weighted addition or subtraction in the time domain. One such circuit, shown in Figure 4, computes the following function:

$$t_{out} = \frac{I_A t_A + I_B t_B}{I_A + I_B} + \frac{CV_{TH}}{I_A + I_B}$$

where t_A and t_B are the rise times of the two input step waveforms and t_{out} is the timing of the output step. The circuit computes a fully continuous analog function using only current sources, digital switches and a comparator.

IV. Conclusion

As has been shown, spike-based processing shows great promise for many engineering applications in terms of improved dynamic range and lower power consumption. Nanoscale implementations of these ideas are being considered in collaboration with Dr. Jose Fortes, also at the University of Florida.

Another direction of interest is to explore the use of these circuits to better understand the biological systems that originally inspired them. An understanding of how nervous systems attain their incredible fault-tolerant performance will lead to further improved engineering systems.

Ultimately it is hoped that future generations of biologically-inspired circuits can be directly interfaced to the brain since they will share similar signal representations and organization. Advanced treatments for such disorders as Alzheimer's, strokes and some kinds of paralysis could become feasible.

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