Analog VLSI and Biological Systems

RLE Group
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http://www.rle.mit.edu/avbs/

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Introduction

Our group's research focuses on BIOELECTRONICS: We work in 3 interdisciplinary areas, **biomedical** electronics, **bio-inspired** electronics, and **circuit modeling** of **biology**. Our work advances frontiers and has applications in 10 different kinds of systems:

1. Ultra-low-power systems
2. Analog systems
3. RF (wireless) systems
4. Micro-sensing (mechanical, optical, fluidic, chemical) systems
5. Ultra-low-noise systems
6. Noise-robust systems
7. Feedback systems
8. Energy-harvesting systems
9. Networked systems
10. Hybrid analog-digital computing and control systems.

Biomedical Electronics

Brain-Machine Neural Prosthetics for the Paralyzed, Blind, Parkinson's Disease and other Disorders

We are working on building wireless, ultra-low-power, highly miniature, implantable brain-machine interfaces that are useful in the treatment of various sensory and neural disorders. Our work is being done in collaboration with neurobiologists and doctors including Professor Richard Andersen's group at CalTech (work on paralysis), Professor Michale Fee's group at MIT (work on experimental neuroscience), Professor John Wyatt's group at MIT (work on the blind), and Dr. Emad Eskandar's group at MGH (work on deep brain stimulation). Thus far, we have built the world's lowest-power neural amplifier, the most energy-efficient near-field wireless telemetry and recharging systems, and highly miniature precise charge-balanced neural stimulators. We have tested a brain-machine interface in a zebra-finch bird and shown that it can wirelessly stop the bird from singing in mid syllable in a reliable fashion. Such in-vivo tests bode well for the potential use of these interfaces in real patients at a later date. Our work leverages off our prior work on cochlear implants for the deaf (See http://www.rle.mit.edu/avbs/ on the Bionic Ear).

Imagers intended for use in a brain-machine visual prosthesis for the blind require extremely good energy efficiency and wide-dynamic-range operation. We have created a low-power wide-dynamic-range imager inspired by the operation of spiking neurons. This synchronous time-based dual-threshold imager experimentally achieves 95.5 dB dynamic range, while consuming 1.79 nJ/pixel/frame. It is one of the energy-efficient wide-dynamic-range energy-efficient imagers reported.

We have developed compression algorithms and encoding strategies for brain prostheses for the blind that are inspired by the operation of cochlear implants. Our algorithm compresses visual information into the basis coefficients of a few image kernels that encode enough information to provide reasonably good image reconstruction with a few stimulating electrodes. Our strategy also uses time-multiplexed stimulation of electrodes to minimize channel interactions like the continuous interleaved sampling strategy used in cochlear implants. These algorithms will enable potential cures for blindness to be implemented with a small number of stimulating electrodes, thus making such treatments more clinically viable.

Bio-Inspired Electronics

An RF Cochlea

The biological inner ear or cochlea is an amazing custom analog computer capable of the equivalent of 1GFLOPS of spectral-analysis and gain-control computations with 14uW of power on a 150mV battery and a minimum detectable signal of 0.05 angstroms. It achieves such efficiency because of the clever use of an active nonlinear transmission line implemented with fluids, membranes, active piezoelectret cells, micromechanics, and electrochemistry. The cochlea has an amazingly large input dynamic range of 120dB, analyzes frequencies over a 100-fold range in carrier frequency (100Hz-10kHz), and amplifies signals at 100kHz even though its cells have time constants of 1ms. Electrically, the cochlea can be modeled as an active, nonlinear, adaptive transmission line with characteristic frequencies that scale exponentially with position. Nonlinear behavior is important in the biological cochlea, particularly for signal detection in noise and gain control.

We took inspiration from the cochlea to create an **RF cochlea** a fast, ultra-broadband, low-power spectrum analyzer. In the RF cochlea, the actions of fluid mass in the ear are mimicked with inductors, the actions of membranes in the ear with capacitors, and the actions of outer hair cells in the ear with active RF amplifiers. We showed that the spectrum-analysis architecture used by the biological cochlea and RF cochlea are extremely efficient: analysis time, power, and hardware usage all scale linearly with N, the number of output frequency bins, versus N*log(N) for the Fast Fourier Transform. We built two RF cochlea chips that operated from 600MHz to 8GHz, with 300mW of power, and had 70dB of dynamic range, making them useful as front ends in software, universal, and cognitive radios for a very broadband range of frequencies. This work has pioneered an important bridge between the fields of hearing and the field of radio-frequency circuits. The work has attracted a lot of media attention since an MIT press release (http://web.mit.edu/newsoffice/2009/bio-electronics-0603.html) and been featured on msnbc.com and more than 50 other news websites.

Circuit Modeling of Biology

Analog circuit models of biochemical reactions

We have developed a highly compact analog circuit that mimics biochemical reactions in cells. To do so, we exploited the detailed similarities between electronics and chemistry to develop efficient, scalable bipolar or subthreshold log-domain circuits that are dynamically equivalent to networks of coupled chemical reactions. This ongoing work is potentially useful for ultra-fast stochastic simulations of large-scale biochemical reaction networks in cells, important in both synthetic and systems biology.

An analog integrated-circuit vocal tract

We have created the first analog integrated-circuit electronic vocal tract, i.e., a chip that 'talks'. A novel resistor circuit enabled the modeling of turbulent and laminar fluid flow in the vocal tract and novel circuits were also used to implement transmission lines in the vocal tract. Our work has led to the concept of a speech-locked loop (SLL), which puts speech synthesis and hearing analysis in a feedback loop to improve speech recognition in noise.

An analog integrated-circuit model of the heart

We have created a CMOS chip that implements an analog electronic circuit model of the heart. This chip is useful in low-power body sensor networks that use analysis-by-synthesis techniques to estimate cardiovascular parameters for medical monitoring.

Publications

Journal Articles

Sarpeshkar, R., W. Wattanapanitch, S. K. Arfin, B. I. Rapoport, S. Mandal, M. W. Baker, M. S. Fee, S. Musallam, and R. A. Andersen,"Low-Power Circuits for Brain-Machine Interfaces," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 2, No. 3, pp. 173-183, September 2008.

Song, Y.A, C. Batista, R. Sarpeshkar, and J. Han, "Rapid fabrication of microfluidic polymer electrolyte membrane fuel cell in PDMS by surface patterning of perfluorinated ion-exchange resin", *Journal of Power Sources*, Vol. 183, No. 2, pp. 674—677, September 2008.

Wee, K. H., and R. Sarpeshkar, "An electronically tunable linear or nonlinear MOS resistor," *IEEE Transactions on Circuits and Systems I*, Vol. 55, No. 9, pp. 2573-2583, October 2008.

Wee, K. H., L. Turicchia, and R. Sarpeshkar, "An Analog Integrated-Circuit Vocal Tract," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 2, No. 4, pp. 316 - 327, December 2008.

Mandal, S., S. K. Arfin, and R. Sarpeshkar, "Sub-uHz MOSFET 1/f noise measurements", *Electronics Letters*, Vol. 45, No. 1, pp. 81-82, January 2009.

Mandal, S., S. Zhak, and R. Sarpeshkar, "A Bio-inspired Active Radio-Frequency Silicon Cochlea", *IEEE Journal of Solid-State Circuits*, Vol. 44, No. 6, June 2009.

Arfin, S. K., Long, M. A., Fee, M. S., and Sarpeshkar, R., "Wireless Neural Stimulation in Freely Behaving Small Animals," *Journal of Neurophysiology*, in press July 2009.

Proceedings of Refereed Conferences

Turicchia, L., M. O'Halloran, D. P. Kumar, and R. Sarpeshkar, 'A Low-Power Imager and Compression Algorithms for a Brain-Machine Visual Prosthesis for the Blind', Invited Paper, *Proceedings of the SPIE*, Vol. 7035, pp. 703510-1:703510-13, San Diego, 10-14 August 2008.

Bohorquez, J., W. Sanchez, L. Turicchia, and R. Sarpeshkar, 'An Integrated-Circuit Switched-Capacitor Model and Implementation of the Heart', Invited Paper, *Proceedings of the First International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL 2008)*, pp. 1—5, October 25—28, 2008, Aalborg, Denmark.

Wee, K. H., L. Turicchia, and R. Sarpeshkar, "An Analog Bionic Vocal Tract", *Proceedings of the IEEE Symposium on Biological Circuits and Systems (BioCAS)*, November 2008.

Arfin, S.K., S. Mandal, and R. Sarpeshkar, "Dynamic-Range Analysis and Maximization of Micropower Gm-C Bandpass Filters by Adaptive Biasing", *Proceedings of the 2009 IEEE International Symposium on Circuits and Systems (ISCAS 2009)*, to be presented, Taipei, Taiwan, May 24 – 27, 2009.

Mandal, S. and R. Sarpeshkar, "Log domain Circuit Models of Chemical Reactions", *Proceedings of the 2009 IEEE International Symposium on Circuits and Systems (ISCAS 2009)*, Taipei, Taiwan, May 24 – 27, 2009.

Other Major Publications

Sarpeshkar, R., "Biomorphic and Neuromorphic Engineering Systems", Invited article, 2009 McGraw Hill Yearbook of Science and Technology.

Invited Lectures

July 2008, 'Bioelectronics', Invited Speaker, Nanostructure Fabrication Gordon Research Conference, Tilton, N.H.

November 2008, 'Bioelectronics', Invited Speaker, IMTEK, University of Freiburg, Germany.

November 2008, 'Bionic and Bio-inspired Sensory and Computing Systems', Invited Speaker, Sensory Perception: Mind and Matter, Austrian Academy of Sciences special workshop, Vienna, Austria.

November 2008, 'Society for Neuroscience', Two Abstracts: 'An Adaptive Algorithm and Micropower Analog Circuit Architecture for Neural Decoding'; 'Ultra-low-power Chronic Wireless Neural Stimulation in the Songbird', Washington, D.C.

February 2009, 'Bioelectronics', Keynote Speaker, CMOS Emerging Technologies Workshop, Banff, Canada.

Theses

Mandal, Soumyajit, *Collective Analog Bioelectronic Computation*, May 2009.