RESEARCH STATEMENT

"Pushing the Limits of Analog Computing and Sensing"

Our research explores new frontiers in unconventional analog computing techniques using silicon and hybrid substrates. The objective is to approach fundamental limits of energy efficiency, sensing and resolution by exploiting computational and adaptation primitives inherent in the physics of devices, sensors and the underlying noise processes.

An overarching theme that is common to all of my research interests can be summarized as "unconventional and hybrid analog computing" and in this short research statement, I will not only reflect on the key highlights of some of these research themes, but I will also describe how they have laid the groundwork for achieving my long-term career goals that are consistent with Washington University's research strengths.

Research in self-powered embedded and implantable circuits and systems

**Background:** Self-powered sensing refers to an energy scavenging paradigm where the operational power of a sensor is harvested directly from the signal being sensed. For example, a piezoelectric transducer could be used for sensing variations in mechanical strain, and the energy from these strain variations could also be used for the computation and storage. As a result, the operation of the self-powered sensor can be asynchronous where events of interest can directly energize the computing and storage circuits. In this manner, the sensor can continuously monitor for events of interest without experiencing any down-time, a feature that can’t be guaranteed with conventional energy scavenging approaches. Our approach to self-powered sensing is to investigate analog non-volatile storage techniques that operate at fundamental limits of energy scavenging (picowatts of power dissipation) and can directly be energized by a miniature transducer element. Based on this principle, we have reported different variants of self-powered health and usage monitoring chipsets that can be embedded inside mechanical structures such as concrete pavements, bridges, propellers, fuselage, biomechanical implants and machine parts. We are also investigating perennial computing devices that can operate by scavenging energy from thermal-noise. Because the power levels of thermal noise are typically less than 1 attowatt (10^{-18})
Nonread out. Acquisition and decoding of the sensor signal is performed offline and any errors due to random interaction and synthetically introduces redundancy into the protein specific forward error potentially be alleviated by improving experimental protocols.

**Current Directions:** Since its inception in 2006, our laboratory has matured the self-powered sensing technology to the point where the devices are currently being deployed in real-world environments. The technology is currently being commercialized by Piezonix LLC, a startup company incorporated in the state of Michigan. For instance, the technology is currently being evaluated in ”smart” civil infrastructure (for e.g. highways) and ”smart” military structures (for e.g. tank treads, gear boxes) within the framework of the ”internet-of-things”. We are currently exploring novel remote interrogation techniques that can be used to retrieve the data stored in the sensor, including harmonic radar based approaches for large infrastructure monitoring and ultrasound based techniques for in-vivo and embedded environments. There are numerous biomedical applications of the self-powered sensing technology which we are exploring at Washington University. These include using the device to understand the evolution of mechanical strain in trauma-fixation devices, leading to the provision of valuable feedback to orthopedic surgeons. An additional research direction would be to explore using an array of embedded self-powered sensors to continuously monitor the statistics of head impacts in helmeted sports like football and ice hockey. The data collected from the sensor could be used in conjunction with other brain imaging techniques to understand the progression of MTBIs (mild traumatic brain injuries). From an engineering point of view, visualization and understanding of the large amount of sensor data could lead to new collaborative research endeavors.

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**Research in neuromorphic sensing, computation and instrumentation**

**Background:** In spite of the remarkable technological advances in micro and nano-scale integration, the performance achieved by specialized biological sensing systems makes even the most advanced man-made systems of today look crude and primitive. At the fundamental level most of the sensory processing in biology is inherently ”analog” and efficiency arises out of exploitation of computing and sensing primitives inherent in the device physics, like diffusion or feedback regulation. Also, unlike man-made sensors, which consider device and sensor noise as nuisances, biology has evolved to use non-linear sensing techniques to exploit noise to its advantage and operate at or below fundamental limits. My research has led to the novel auditory sensing and bioinstrumentation that use noise-exploitation and non-linear techniques to achieve very high energy-efficiencies and robustness. For example, my research group has reported a silicon cochlea that exploits jump-resonance type non-linearity in analog filters to achieve robustness in the presence of noise. Another type of neuromorphic instrumentation reported by my research group exploits neuronal type noise-shaping and adaptation techniques to achieve high-resolution, precise signal acquisition and noise cancellation.

**Current Directions:** There are three main research directions that we are currently pursuing in the area of neuromorphic sensing. The first direction is to investigate portable and miniature bioinstrumentation that can monitor physiological markers of interest by scavenging energy from human motion or human temperature gradients. In this regard, noise-cancellation and motion artifact compensation techniques that have been developed by my research group would play an important role. The second direction is to investigate high-resolution measurement techniques in miniature sensor arrays (microelectrodes, acoustic or electrochemical) using a combination of spatial adaptation and noise-shaping techniques. The third collaborative research direction that we are pursuing is to investigate analog VLSI techniques to emulate and understand large-scale and complex dynamics that are observed in biological systems.

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**Research in forward error-correcting proteomics**

**Background:** Design of reliable and multi-analyte protein assay requires understanding, modeling and characterization of fundamental noise, stochastic interactions between proteins, and device artifacts. While the effects of variability could potentially be alleviated by improving experimental protocols and device fabrication processes, we are investigating a forward error-correcting (FEC) approach to improve the reliability of biosensors. My approach has been to use non-specific protein-based hybridization circuits (using antibodies, aptamers, or DNA) in conjunction with a transducer which converts the binding of an analyte with the protein into a measurable optical or electrical signal. A biomolecular encoder synthetically introduces redundancy into the protein-protein interaction before the signal generated by the transducer is read out. Acquisition and decoding of the sensor signal is performed offline and any errors due to random interaction and non-specific binding is compensated. While we have successfully demonstrated the feasibility of the FEC assays using
small scale experiments, the full potential of an FEC biosensor can only be realized using large-scale biomolecular encoders that integrate millions of protein-based circuits. In this regard, we are investigating a simulation framework that could be used to model, analyze and predict the reliability of large-scale biomolecular encoders without resorting to laborious and expensive experimental procedures. The result is an open-source computer-aided design (CAD) framework called FAST (Factor-graph based Analysis of Stochastic circuIts), that can be used for design, synthesis and verification of large-scale hybrid protein-silicon circuits.

**Current Directions:** We are currently investigating extensions of FAST that will lead to different designs of synthetic antibodies and yield the best possible error correcting capability in proteomic assays. In addition to the error correcting capability, the use of combinatorial biological probes could lead to a generic diagnostic platform that could detect signatures of multiple and, more attractively, "unknown” pathogens. The high-dimensional signatures could then be used in conjunction with machine learning techniques to determine the presence or absence of a target. An additional research direction that we are pursuing in the area of FEC biosensor technology, involves development of the ability to detect "co-morbid” conditions where symptomatic effects due to one pathogen are masked by another pathogen or an unrelated condition (for example tuberculosis in HIV patients). Co-morbidity is a particularly important problem in elderly patients who suffer from multiple pathologies and are more prone to infections.

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**Background:** Conventional analog and digital VLSI design methods typically follow a top-down approach where proven algorithms are mapped onto an optimized computing hardware. In this research, my goal has been to investigate an unconventional bottom-up approach where computing paradigms that are inherent in hardware can be used for designing specialized algorithms. This is particularly relevant for analog VLSI (aVLSI) where the computation is always approximate and is strongly dependent on the device physics. My objective has been to use universal conservation principles (charge, mass or current) to approximate well known functions, and to then appropriately modify the algorithms to achieve the desired or even superior performance. As a part of this research, I am also exploring novel analog non-volatile memories, based on floating-gate transistors that operate using transistor leakage currents (pico and femtoamperes currents). We have reported ultra-compact floating-gate current memories that can achieve less than 100ppm/K of temperature stability, as well as floating-gate voltage bias generators that can be programmed at a resolution greater than 13 bits. Using these basic analog memory elements we have designed analog system-on-chip solutions that implement machine learning architectures like support vector machine classifiers and hidden Markov models. My research has shown that many of these nano-watt analog processors can achieve energy-efficiencies that are two orders of magnitude better than the state-of-the-art digital processors.

**Current Directions:** In this area, my research group is currently scaling the previously developed analog designs into large-scale computing and pattern recognition systems. This requires the use of hybrid approaches where the computational workload is carefully balanced amongst different analog processors that communicate with each other using binary spike trains, similar to neuromorphic systems.

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**Representative Publications (A complete list of publications can be found at [http://www.egr.msu.edu/aimlab](http://www.egr.msu.edu/aimlab)**


