Invited Paper

An Overview of Research in Advanced Microelectronics for Micro-Autonomous Platforms

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ABSTRACT

The Army Research Laboratory established the Micro Autonomous Systems and Technology (MAST) Collaborative Technology Alliance (CTA) program in 2008 to leapfrog technological barriers toward achieving the autonomous operation of a collaborative ensemble of multifunctional, mobile microsystems. This goal will be realized through fundamental advancements by the MAST alliance, composed of four centers with focused research activities in Microsystems Mechanics, Processing for Autonomous Operation, Microelectronics, and Integration. A team of researchers assembled by the University of Michigan was chosen to lead the microelectronics center. This paper provides an overview of research activities in the MAST Microelectronics Center. Research activities in this center are organized around five major research thrusts: 1) sensing, 2) low power processing, 3) communications, 4) navigation, 5) efficient power generation.

Such activities are envisioned to enable micro-autonomous sensor platforms by developing novel electronic sensors and devices having the following attributes: low power and power efficient characteristics, low mass and volume, enhanced functionality/sensitivity, survivability, durability, extended operation capability, low cost, and fault tolerance. Fundamental advances in microelectronics will be accomplished through implementation of bio-mimetic and bio-inspired techniques and technologies, utilization of Nano/micro fabrication processes, and incorporation of novel materials in fabrication of components and subsystems.

Keywords: autonomous robots, radar, software-defined radio, low-power, MEMS, BST, geiger, quantum-dots, solar cells, transpiration, miniature antennas

1. INTRODUCTION

The research program outlined here presents a clear vision for development of critical microelectronic technologies for enabling The Army to develop and deploy micro-autonomous systems for urban battlefield environments. The five thrust areas of research entail novel electronic circuit/processing architecture, novel materials for communication and power-efficient sensing, low-power communication and networked response, assisted and autonomous navigation, as well as power generation and management. Revolutionary multidisciplinary research based on bio-inspired and bio-mimetic approaches are proposed to achieve breakthroughs in military relevant system and sub-system specifications such as size, weight, power consumption, and sensitivity.

For example, in the area of micro sensors, a bio-mimetic micro-gas-chromatograph using MEMS techniques as well as advanced materials is being developed that will enable detection of trace amounts of hazardous chemicals or explosives in the atmosphere with very low power (<10mW) and high sensitivity (≈1ppb/analyte). New materials and architectures are also being explored for use in a miniaturized gas-based radiation sensor, utilizing micro cavities and high-Z metal layers for detection of gamma rays and Beta particles within a volume as small as 0.15cm^3 and sensitivities comparable with existing handheld detectors. In the sensor area we are also developing a novel bio-mimetic HAIR technology that makes use of novel materials and actuation to mimic the hairs on skin, enabling a whole range of new devices, including highly-sensitive touch and flow sensors, and thermal regulation using actuated heat-exchanging hairs.

The entire team has contributed to this effort, they are: Khalil Najafi, Ken Wise, Yogesh Gianchandani, Dennis Sylvester, David Blaauw, Amir Mortazawi, Clark Nguyen, Michael Flynn, Jack East, Michel Maharbiz (Berkeley), and Luke Lester (Univ. of New Mexico). Further author information: (Send correspondence to saraband@umich.edu)

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For low power, onboard processing we are exploring a bio-mimetic strategy using massively-parallel processing schemes to achieve a 100X power reduction over the current state-of-the-art, while achieving a computational capability of 100GOPS (Giga Operations Per Second). The dramatic power reduction is accomplished through a variety of techniques on the transistor-level, circuit-level, and architecture-level. A key element is the use of circuit structures capable of operating at ultra-low supply voltage (100 - 200mV) combined with noise-suppression circuits to address variability in the operation regime and advanced parallel and pipelined architectures to address performance needs.

Platform communication is accomplished by development of a single-chip wireless transceiver front-end that can communicate over any frequency band from 100MHz to 5GHz, utilizing any one of a variety of commercial or military standards. This highly-configurable software-defined radio system uses breakthrough research in several different areas: novel deposition and utilization of advanced materials such as BST for filters; silicon micromachining and MEMS devices for resonators, filters, and mixers; bio-inspired, low-power, massively-parallel analog-to-digital converters with built-in redundancy for robustness against failures; and advanced 3D metamaterials used for antenna miniaturization. Novel fabric and composite materials will enable incorporation of low-frequency and wideband antennas into the structural frame of the platform (load-bearing antennas).

Two entirely novel methodologies, one based on biomimetic transpiration, and the other based on the application of quantum dot solar cells, are pursued for power replenishment within the platform. Evaporation of "sweat" over the platform "skin" pulls a water/oil mixture past an array of capacitors, changing the capacitance and generating useful power. High efficiency Q-dot solar cells are enabled by introducing the high bandgap barrier of the DFENCE structure, to suppress nonradiative recombination, pushing efficiencies above 30%.

The sensor must autonomously navigate, both to find targets of interest and to avoid collisions. Novel 3D packaging concepts will be researched to enable a navigation grade MEMS-based Inertial Navigation System. This will be augmented by research into a light-weight biomimetic imaging radar system at 215 GHz that mimics the bat echolocation sense. The entire RF front-end of the radar system is designed to weigh less than 2 grams. Together these two major advances will enable low-power, highly-accurate navigation, collision-avoidance, and 3D mapping.

The research topics discussed above are presented in more detail below, organized by platform subsystem. Note that we do not discuss here aspects of the research program that are covered by the other centers in the Consortium, such as algorithms for control at all levels, mechanics, and actuation.

2. POWER SUBSYSTEM

Vision: The proposed system will employ two different and complementary power scavenging systems as well as a battery, a supercapacitor and power conditioning circuitry.Along with the battery, supercapacitors will be used for storing power and also for providing peak current. The energy scavengers will provide a means for recharge of the batteries and supercapacitors while deployed. The battery will be used during periods when the capacitor is not charged and there is not enough power from the scavengers. The associated circuitry will perform power regulation and delivery to the other units on the system. There is significant work in the industry on supercapacitors for use in a variety of applications involving consumer electronics. We will utilize the developments in this field rather than develop our own supercapacitor technology. The center will focus on two specific approaches in power scavenging: Quantum-dot solar cells and transpiration-based power generation.

2.1 Scavenging power from light: Quantum-dot Solar Cells

This research is being carried out by a team composed of Prof. Forrest and Dr. Zimmerman at the Univ. of Michigan, and Profs. Lester and Malloy at the Univ. of New Mexico.

Relevance: The longevity of many electronic sensors in battlefield environments relies on their ability to replenish their energy reserves. Solar radiation is a major source of energy that is often available and that can be utilized for this purpose. This will allow for mission durations that are much longer, allowing the platform to rest and recharge before continuing.

Current State-of-the-art: Current manufacturing methods produce solar cells from polycrystalline silicon with efficiency values in the rage of 12 to 15 percent in converting sunlight to electricity. For small platforms with constrained size and weight limitations it is highly desirable to double or triple the solar cell efficiency.

Research Goals: The objective of the quantum solar cell task is to realize high-efficiency semiconductor solar cells for energy scavenging based on a high-density (QD) ensemble within a wider-bandgap matrix. Due to 3D confinement, QD absorbing regions offer a significantly reduced hot carrier relaxation rate due to the so-called phonon bottleneck compared to carrier extraction rates, and, thus, have the potential for very high efficiency and compact size. The QD solar cell project will investigate theoretical and experimental issues including (1) examining the underlying physics of high efficiency solar cells that implement QDs and intermediate bands, (2) the UMich-proposed QD DFENCE[1] solar cell structure, (3) designing and fabricating an advanced QD solar cell with efficiency values around or greater than 40%.

2.2 Scavenging power from transpiration

This research is being conducted by Prof. Maharbiz at the Univ. of California at Berkeley.

Relevance: In order to allow for battery recharging while in operation, transpiration-based power generation promises to be a high-power method which is significantly lighter than current solar cells. This will allow for mission durations that are much longer, providing the possibility for resting and recharging before continuing.

Current state-of-the-art: We recently demonstrated how the basic concept of harnessing microscale liquid-gas interfaces could be used to extract work with a method inspired by dispersal of spores by ferns. As water dries inside cells, surface tension between water and cell wall gives rise to high forces along the interior walls of the cells, leading to a sudden opening of the spore-sac. Our devices were batch fabricated out of photopatternable silicone using conventional microfabricated processes. When wetted, the microdevices repeatedly and reproducibly deflected many millimeters.

Research Goals: The goal of this part of the project is to design, fabricate and test a revolutionary bio-mimetic energy scavenging microsystem inspired by the transpiration mechanisms in plants. These devices would scavenge power from a variety of humidity gradients present in most environments.[2]

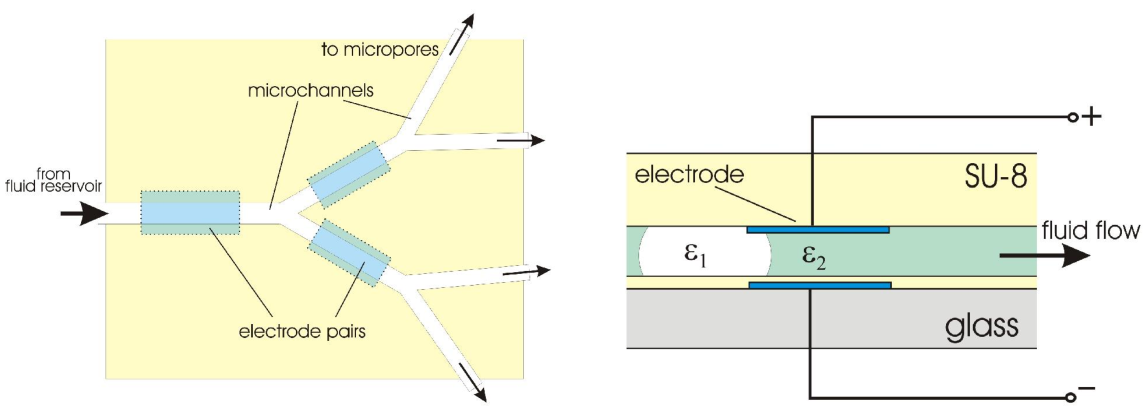

Figure 1. a) Schematic top view of energy scavenging device; fluid networks branch according to Murray's Law for maximum conductance b) Schematic cross-section. As bubbles or droplets are carried between the capacitor plates, the change in capacitance can be used to 'pump' the plates and generate electrical power.

We will develop devices with dozens to hundreds of inter-locked, water microchannels (Figure 1a). One end of the network will be open to the atmosphere through microscale pores (1-50μm); the other end of the network will draw water from a reservoir. Evaporation will take place at the microscale pores and induce flow towards the micropore end.[3] In order to use this flow to generate power, we first fabricate pairs of microfabricated electrodes into the microchannels along the 'floor' and 'ceiling', producing a capacitor.

Each of these capacitors would be charged when the microchannels are filled with water. As water begins to flow, air bubbles are pulled along the microchannel (Figure 1b), causing a drastic decrease in the capacitance as they pass an electrode: up to a 10^3 change, due to the change in the dielectric constant.This change in capacitance can be used to charge the parallel plate capacitor: for a fixed charge a decrease in capacitance will increase the voltage across the plates (since V = Q/C).

3. NAVIGATION SUBSYSTEM

Autonomous navigation requires many different sensors and related processing techniques. Inertial sensors can be used for short-term dead-reckoning of position. GPS can be used when not corrupted by multi-path or occluded inside caves or buildings. Imaging sensors can be used for mapping the local 3D landscape, including buildings, vegetation, and other obstructions. This local sensing is very important for three main reasons: collision avoidance, landmark identification, and surveillance. Another type of sensing involves relative position with respect to other sensors and soldiers. Integration of these disparate sensing mechanisms into a functional subsystem requires high-speed, low-latency processing and sensor fusion to allow fast responses to threats. We envision that COTS technology can be used for the following components: stereo video, imaging IR array, and radio triangulation.

In order to provide high-resolution imaging and collision-avoidance when reflected sunlight is scarce, we propose to conduct research into all the components that are necessary, and to develop and build a new high-resolution imaging radar, able to provide a 3D representation of the local area. We also will conduct research into building highly-sensitive arrays of hair-like sensors. These could then be used in biomimetic inertial sensors such as those found in the mammalian inner-ear. This research is described later in the section on the Sensor Subsystem.

3.1 mm-wave Radar

This research is being conducted by Prof. Sarabandi at the Univ. of Michigan.

Relevance: Taking our inspiration from the bat echolocation navigation system we propose to conduct research into the necessary technology to enable development of a lightweight and compact millimeter-wave (MMW) based beamscanning radar, allowing the sensor platform to "see" in conditions that make the use of passive optical sensors difficult or impossible. In addition to imaging, the radar also provides the relative speed and acceleration of the platform and moving objects. The bock diagram of such a system is presented in Fig. 2.

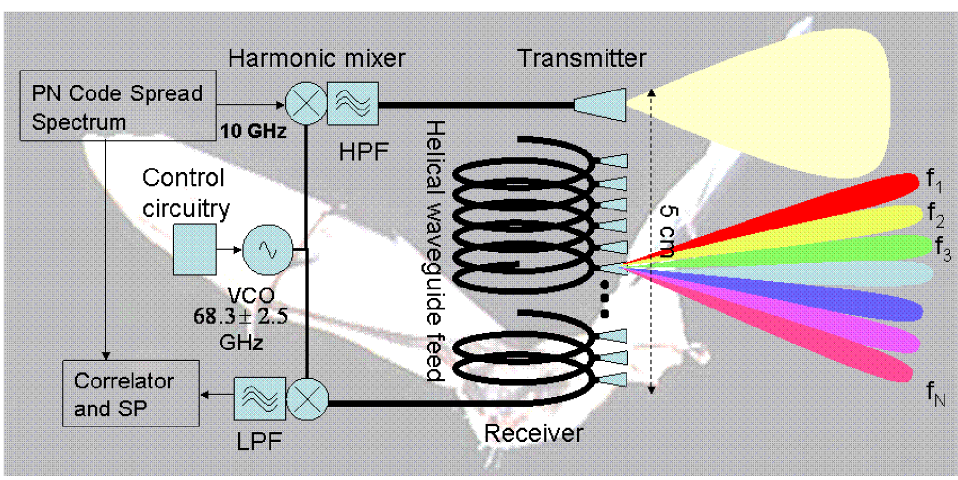

Figure 2. Bat-like navigation system based on a Y-band (215 GHz) radar.

Current State-of-the-art: Existing imaging radars make use of either mechanical or electronic beam steering. Mechanical beam steering radars are often very slow, bulky, and susceptible to mechanical failure. Electronic beam steering radars, on the other hand, are fast but rather expensive and power inefficient, requiring several Watts of power, and several pounds of specialized hardware.

Currently there are no technologies available for electronic phase shifters at the upper mm-wave spectrum. Hence an alternative revolutionary approach for the design of very high frequency radars with beam steering capability is the subject of our research.

Research Goals: The revolutionary approach is to combine ideas from signal processing, electromagnetics, and micromachining technology to enable an operational low-cost, low power, lightweight Y-band radar with beamsteering capability. We envision the use of a frequency-coded pulse that will allow range and direction of various targets to be determined. This can then be integrated into a 3D local-area map for navigation and path-planning purposes. This system will allow the platform to navigate and see where passive optical systems cannot operate.

The system block diagram of the proposed radar system is shown in Fig. 2. For system simplicity, low processing requirements, and low power consumption, we propose a frequency scanning system. In this system the receiver antenna is fed by a helical leaky waveguide. As the frequency is scanned (from 207.5 GHz to 222.5 GHz) a progressive phase is formed along the radiating elements, providing for a $\pm 15°$ scan. Frequency scanning can easily be accomplished using a VCO that drives the up- and down-converters using harmonic mixers. Using a binary phase shift key (BPSK) pseudo noise (PN) code modulated waveform at 10 GHz with 500 MHz bandwidth provides range and speed.

To achieve a narrow beamwidth in elevation, we will use an array of cascaded very low-loss planar dielectric resonators coupled to the slotted waveguide feed. We will extend the ceramic stereo-lithographic method for monolithic fabrication of dielectric resonator array at 215 GHz.[4,5]

4. COMMUNICATION SUBSYSTEM

The primary goal is to develop new methods for, and demonstration of a, single-chip wireless transceiver front-end that can communicate (or eavesdrop) over any frequency band from 100MHz to 5GHz, utilizing any one of a variety of commercial or military standards (e.g. NTDR, JTRS, GSM, WiFi etc). This flexibility is possible through a combination of switchable filtering (MEMS and BST) and high performance analog-to-digital conversion. Efficient miniaturized antennas, power amplifiers and direct digital modulators also contribute to this goal. We also will develop a fully-integrated single-chip ($<$2mm^3) wirelessly-networked sensing node. These sensing nodes will be deployed (dropped) by the platform and communicate back to the platform, or with other nodes through an ad-hoc network of sensor nodes.

4.1 *Any-band* Wireless Transceiver

This research is being conducted by Prof. Michael Flynn at the Univ. of Michigan.

Research Goals: The transceiver should be able to switch and adapt rapidly between many different communication schemes, using less than 10mW. The entire transceiver including a high frequency antenna will be integrated on a single integrated circuit ($<$25mm^2). Lower frequency antennas will be built in the platform structure.

Moving the analog-digital interface close to the antenna greatly improves the flexibility and adaptability of the receiver. An entire RF band-of-interest is mixed down and digitized. Channel selection is implemented in the digital domain allowing the receiver to switch almost instantly between channels and between modulation schemes. New approaches to analog-to-digital conversion will be pursued to improve A/D conversion performance by an order-of-magnitude.

4.2 Maple Seed Radio

This research is being conducted by Prof. Sarabandi at the Univ. of Michigan.

Relevance: Having a wireless sensor that can be dropped from the mobile platform during flight would enable several novel scenarios, including: 1) making an invisible curtain around an encampment, with each radio signaling its neighbor, noting when any loss of signal occurs, possibly signaling an intruder; 2) leaving a trail in a complex environment (cave, urban) to follow back home; 3) distributed sensing of movement, vibration, people, as they pass near any of the sensors.

An off-center Maple tree seed attached to a single wing allows for helicopter-like aerodynamics once the seed falls from the tree, decreasing the force of ground impact by nearly 99%, as compared with no wing. We propose a wireless sensor to emulate this seed, containing a battery, a radio, an antenna, and a sensor. Each airborne platform would hold 50 or more of these sensors, and would be able to drop them while flying.

Research Goals: The wingspan will be about 5 cm, 1mm-thick, and half the weight will be concentrated in the seed at one end. The radio antenna will be placed in the wing which will be actuated using water surface tension (to save on electricity). This allows the antenna to be raised vertically after landing in order to significantly improve near-earth wave propagation.[6] The separate seeds will be able to network among themselves and with the platform as needed.

Research Activities: The major research topics for making this vision a reality are: 1) design of antenna, integration into wing, 2) design and implementation of a low-power wing-erector, 3) low-power processor, 4) low-power, miniaturized single-band radio, 5) packaging.

4.3 Micromechanical RF Signal Processors

This research is being conducted by Prof. Nguyen at the Univ. of California at Berkeley.

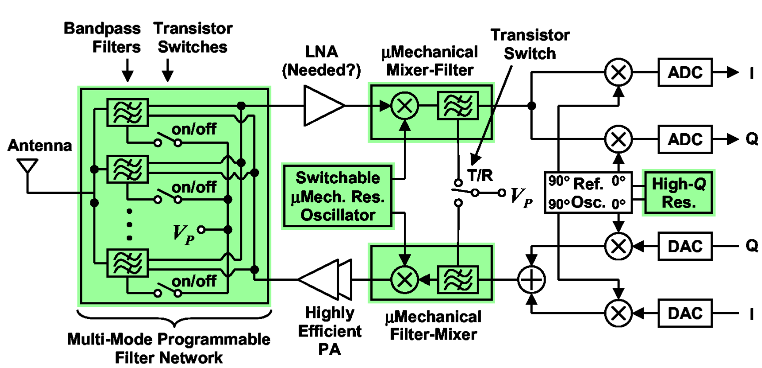

Figure 3. System-level block diagram for the low-power MEMS-based transceiver front-end architecture of this proposal, identifying the functional blocks to be implemented via micromechanical signal processors.

The architecture of Fig. 3 utilizes high-Q, low-loss μmechanical signal processors wherever possible to implement not only frequency filtering, but also mixing, T/R switching, phase-shifting, and frequency generation. The use of passive μmechanical circuits rather than transistor circuits to implement these functions greatly reduces power consumption in the receiver, since the dc and dynamic power required by transistors is eliminated. In addition, the μmechanical circuit versions offer superior noise performance and substantially higher dynamic range than attainable via transistors, enhancing their robustness under hostile operating conditions (e.g., high jamming environments). As a quick example, VHF μmechanical resonators have been measured with IIP3's better than 40 dBm, which is more than 40 dB better than typical transistor circuits. Even higher values are expected at UHF. In addition, the Q>10,000 of the micromechanics allows filter insertion losses <1dB, even for bandwidths small enough for RF channel-selection, and this greatly improves the overall receiver noise figure.

4.4 Switchable BST filters

This research is being conducted by Prof. Mortazawi at the Univ. of Michigan.

We will develop a new class of Film Bulk Acoustic Resonator (FBAR) filters based on thin film ferroelectrics, in particular, Barium Strontium Titanate (BST) for the design of reconfigurable transceivers. Using thin film BST for the construction of high frequency tunable filters offers a host of advantages: 1) Good long-term stability at operational temperatures and voltages; 2) Integration with RF ICs, ability to leverage semiconductor technology to make devices ; 3) Low losses resulting in high quality factors; 4) Negligible dispersion in high quality films; 5) No junction noise (unlike Schottky and varactor diodes); and 6) Small footprint.

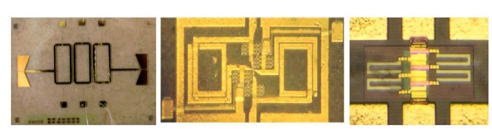

Figure 4. BST-based tunable-filter, phase shifter, and stacked capacitor for linear and high-power operation.

During the past several years we have successfully fabricated high quality BST varactors (Q = 100) at microwave frequencies. Furthermore we have demonstrated integrated BST based tunable matching networks, filters, linearizers and phase shifters.[7–10] We will use BST switchable bandpass filters to enable efficient, low power integrated reconfigurable transceivers. These BST switchable filters rely on the electrostrictive effect in BST material which recently has been observed by us and by other researchers.[11,12]

Because of the electrostrictive effect in the thin film BST, the acoustic resonance within BST film can be turned on and off by application of a dc electric field. The switching mechanism based on electrostriction does not degrade the RF performance, and does not consume power due to the fact that no current is drawn, thereby the loss and cost issue as compared to semiconductor switches is eliminated. Furthermore one can turn on and off tens or hundreds of filters using this property, something that is impractical with GaAs switched matrices.

4.5 Structural and Miniature Antennas

This research is being conducted by Prof. Sarabandi at the Univ. of Michigan.

This task proposes novel VHF and UHF structural antenna techniques and new techniques for miniaturized higher frequency antennas. The EM spectrum from VHF through S-band is commonly used to take advantage of its considerable penetration through buildings, wave diffraction around obstacles, and wave propagation over curved surfaces. To reduce the air drag and the volume occupied by a low frequency (VHF-UHF) antenna, conformal antennas with low-profile are highly desirable. We will pursue the revolutionary idea of incorporating low frequency antenna structures as an integrated part of the platform, often called a load-bearing antenna (LBA). Of special interest are novel antenna architectures that are not only compact, wideband, and highly efficient but also *monolithically integrated into the primary structure of the platform.*

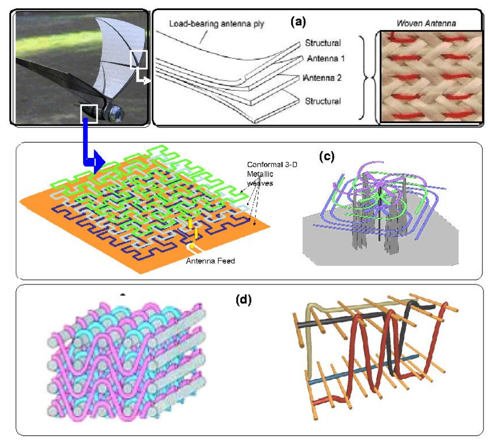

Figure 5. Integrated load-bearing antennas made of hybrid composites with embedded metallic weaving.

Specifically, a dual-thrust approach for research into LBAs will be pursued. In the first thrust, multilayer planar antennas will be realized using existing prepreg-based construction methods, modified to incorporate metallic grids, and traces to form radiating elements. In the second thrust, complex 3-D integrated antenna elements (space-filling antennas) will be realized by weaving conducting fibers into a structural textile composite.

For higher frequency radio applications such as the proposed Maple Seed sensing node (Section 4.2) for which the size of transceivers is very small and the cost of fabrication has to be low, we will need to integrate antennas with the rest of the RF transceivers in a single chip. This eliminates the need of having external transmission line connections or sophisticated packaging, which can reduce the cost of such systems considerably.

5. SENSOR SUBSYSTEM

While power, locomotion, embedded signal processing, and wireless communication are all necessary parts of the proposed microsystem, intelligence gathering is their reason for being; thus, sensors are the heart of the system. Several imaging sensors are part of the platform and have already been described as part of the Navigation Subsystem. Acoustic sensing is also important, and we will use commercially available microphones in a configurable array, allowing for attention to be focused in any direction. We also expect to use commercial sensors for sensing of platform state: current sensors for power usage, strain gauges for mechanical status, and temperature sensors for internal variability. The proposed nuclear, chemical, and HAIR sensors are key to military applications and are where our research efforts will be focused. These constitute revolutionary breakthroughs. The radiation sensor is as much as three orders of magnitude smaller and lighter than previous devices using little power with improved sensitivity and operating life. The proposed chemical sensor, a gas analyzer incorporating a micro gas chromatograph (μGC), is also orders of magnitude smaller, cheaper, and faster than previous devices. Embedded in the mobile platform, such devices could be a breakthrough in IED detection. These proposed sensing devices thus target some of the most critical needs in urban warfare. Hair-like sensors are bio-mimetic microsystems that enable sensors on movable thin protrusions. Our research will focus on making them useful in two application areas: 1) touch sensors, which could be applied to the outer body to sense atmospheric forces, and also contact forces; and 2) inertial sensors in configurations similar to that found in the mammalian inner ear.

5.1 Chemical Sensing

This research is being conducted by Prof. Wise at the Univ. of Michigan.

Relevance: Being able to sense airborne chemicals will allow the sensor platform to detect things of military importance, but will also enable it to track the smell to its source. These functions are very important for sensing explosives, smoke, and gasoline, to name but a few. IED standoff detection can be accomplished by having an airborne platform fly into and near suspected areas to collect air samples, and test as it flies.

Current state-of-the-art: Work on the μGC of Fig. 6 has been underway at Michigan for six years under the NSF-funded Engineering Research Center for Wireless Integrated MicroSystems (WIMS ERC) (2000-2010). The proposed work builds on that effort.

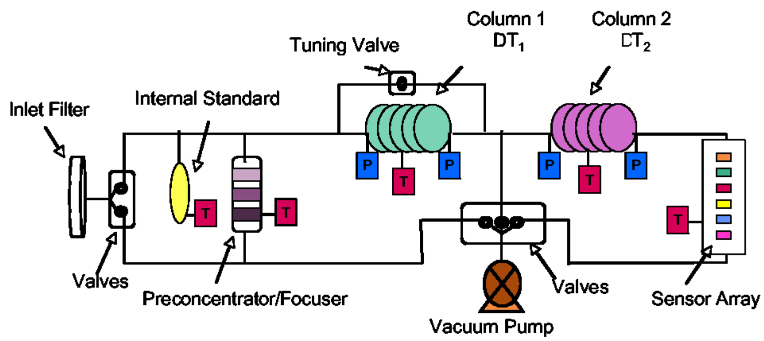

Figure 6. Diagram of a μGC.

While most airborne chemical sensors are the size of a shoebox, our research version is significantly closer to the size, weight, and power usage goals for a mobile robot.

Inlet filters, preconcentrators, microvalves, separation columns, detectors, and micropumps have all been demonstrated.[13]

Research Activity: In Fig. 6 a preconcentrator is used to capture a sample of ambient air that is then rapidly desorbed into the column, amplifying the sample concentration. Different gaseous species spend different amounts of time adsorbed on the column coating so that they emerge from the column separated in time and can be detected using an array of chemiresistive sensors. The delay identifies the species present, while the area under the response curve indicates the quantity present.

5.2 Nuclear Radiation Sensing

This research is being conducted by Prof. Gianchandani at the Univ. of Michigan.

Relevance: The proposed radiation sensing subsystem represents a new class of micromachined gas-discharge sensors that can provide superior performance using a variety of scaling advantages and also provide wireless signaling without the need for interface electronics and without the consumption of additional power.

Current State-of-the-art: Preliminary proof-of-concept has been obtained using NSF support. Radiation from ^{204}Tl sources has been detected, and in-situ signaling bandwidth up to 3 GHz has been demonstrated. The proposed structure is new and significantly enhanced.

Research Activities: Gas-based radiation sensors utilize a gas cavity with a high electric field. Incident beta particles, which are essentially high-energy electrons, trigger avalanche current. These gas-based detectors are the preferred sensors for detecting ionizing radiation in the field[14] because they are rugged and reliable, temperature insensitive, require only simple circuitry, and measure over a wide range of radiation species and energies. The avalanche current discharge that is produced in gas-based radiation sensors can also be exploited for wireless communication.

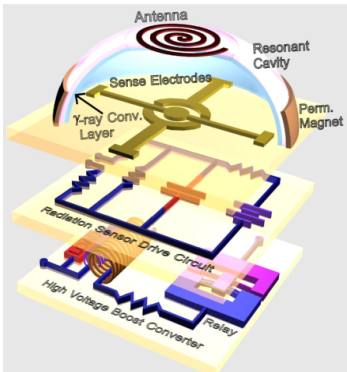

Figure 8. Conceptual schematic of the proposed radiation sensor and wireless transmitter.

Figure 8 illustrates several features of the proposed device: a three-electrode sense scheme, a glass substrate, a permanent magnet, a resonant cavity, a gamma-conversion layer, and an antenna. The low-capacitance three-microelectrode geometry utilizes a "floating" electrode to improve detector sensitivity and response time [8]. The middle electrode, which is powered initially by field emission and leakage currents, rapidly quenches the discharge. Another component is the arrangement of permanent magnets, which enhance the RF generation. The structure operates as a resonant cavity with an integrated antenna, providing filtering, amplification, and narrowband transmission of the RF signal in the 10-30 GHz range.

5.3 High-performance Actuation and Integrated sensing Research (HAIR)

This research is being conducted by Prof. Najafi at the Univ. of Michigan.

Relevance: Hair-like structures have taken many forms in nature and are used extensively to achieve a variety of functions including deflection, which we are investigating in this research. Hair offers: 1) a larger surface area than a flat chip, allowing it to interact with the external environment efficiently; 2) the ability to be raised or retracted to accentuate/minimize the needed function.

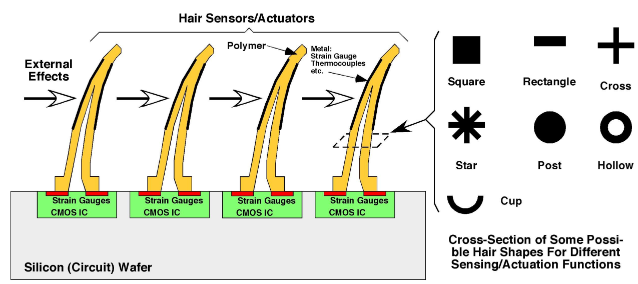

Figure 9. Proposed structure of HAIR, an arrayed structure consisting of a large number of hair elements used for sensing and actuation.

Current State-of-the-art: Using a hair as a tactile sensor (sensing deflection) has been accomplished[15] with 4×4 arrays of cylindrical hairs of 500 μm diameter, 3000 μm tall with sensitivities down to 3 μm tip deflection at a tip load of 25 μN (0.25 kPa) with 0.1 sec response time. This contrasts with spider tactile sensors having 30 μm tip deflection and tip loads of 50 nN. The difference can be related to the torsional stiffness of the biological vs. artificial hairs. Current research on conformable touch arrays using organic transistors are somewhat faster (0.03 sec response time) but have a low sensitivity (30 kPa).[16]

Research Goals: We plan to use this hair concept to target several different devices, all based on deflection: Tactile sensors will have 10-100 times the force sensitivity, and conformable arrays of 100×100 hairs. This will allow sensing of winds, touch, tactile imaging of contact surfaces for improved perching behavior, or even damage sensing. Fast-response, reflex-like reactions to extreme conditions, such as high force or high temperature, are then made possible with a connection to the appropriate actuators to steer the platform away from the hazard. These can then be integrated into liquid-filled geometries, mimicking those found in the mammalian inner-ear, to allow sensing of angular and linear acceleration.

Research Activities:

The overall concept of artificial hair arrays with integrated sensors and actuators is shown in Fig. 9. Each hair is constructed on top of its own integrated CMOS circuit block for measurement, control, and signal processing, thus forming a Hair Sensing/Actuation Element (Hexel). The signals generated by the hair can be transduced with piezoresistive sensing, using on-chip MOS-based strain gauges is the most desirable for sensing flow, acceleration, and vibration. We expect to form the hair structures on a separate wafer and then transfer the large array of hairs from that wafer to a second wafer that contains all of the CMOS circuits needed to interface with and process the hair information.

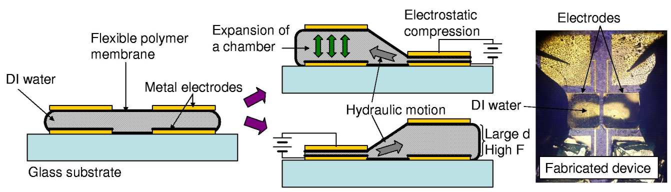

Figure 10. (Left) Operation principle of a hydraulically-amplified electrostatic actuator and (Right) the fabricated actuator with encapsulated DI water inside.

We propose a unique and revolutionary new micro-actuation technology connected to each hair based on microhydraulics and electrostatic actuation to obtain large-force, large deflection, and low-power actuation (Fig. 10). This new class of actuators utilizes a liquid dielectric for hydraulic amplification and force transfer. Each parallel-plate chamber can be compressed by pulling down a flexible membrane using electrostatic actuation, thus forcing the liquid under it into the adjacent chamber, causing that chamber's membrane to be moved out of plane. The existence of the liquid in the gap serves two functions: 1) the large liquid dielectric constant produces a larger electrostatic force than is available in air-gap electrostatic actuators; and 2) the liquid acts as the hydraulic liquid that transfers the large electrostatic force, and can be utilized for hydraulic amplification. Intuitively, think of a deflated balloon as the base of the hairs that are flattened to the surface, when pressurized, the balloon's walls stiffen, and the hairs are raised. Fabricated electrostatic liquid-gap (de-ionized water) actuators[17] utilizing Parylene with hydraulic amplification measuring 2×2 have produced out-of-plane deflection of 36.7μm, using 320V actuation voltage (Fig. 10), a force of about 1mN.

6. PROCESSING SUBSYSTEM

A key element of unmanned vehicle navigation and data acquisition is ultra-high performance data processing capabilities. To allow integration of such processing capabilities in a small air or ground vehicle with today's or near future power technologies, *one or two orders of magnitude of power reduction* must be obtained over current data processing technologies. We therefore will develop a new and disruptive approach to digital VLSI data processing that enables GHz processing in the mW range, instead of the current use of multiple Watts.

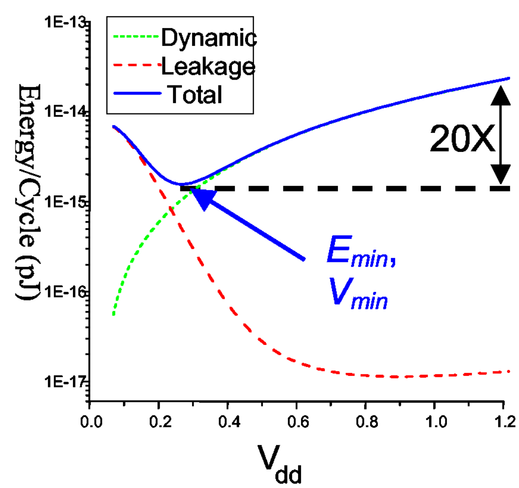

Figure 11. Energy per clock cycle shows a distinct minimum with supply voltage due to growing clock period at subthreshold supplies.

The key research task is the co-development of novel circuits and architectures for efficient execution of algorithms required by other key research tasks. In particular, we expect that the following functions will benefit from specific architectures devoted to their processing needs: imaging: segmentation, stereo depth perception, motion detection, compression; communication: filtering, coding, channeling; navigation: inertial filtering, 3D pose estimation, fusion, triangulation; and chromatograph sensor processing.

In addition to the task-specific signal processing modules, 100 or more simple in-order pipeline cores will be included to provide general purpose parallel processing power - these will operate at frequencies in the 10MHz range at 200mV in 45nm at ≈10μW, hence providing reasonable general computation capabilities at 1mW power levels. One hundred simple processor cores in 45nm will consume only ≈1-2mm^2.

Data storage requirements will be kept modest for a system of this size - on the order of several Mb. Techniques including data compression, new memory topologies and sleep management strategies, will enable this relatively small memory footprint. Memory throughput can be aided by the use of higher supply voltages than the processing elements; this also puts the low activity memories at their natural energy-optimal operating voltage. At an expected traditional memory density of 4Mb/mm^2 in 45nm, even given the expected area increases required to achieve low-voltage operation and robustness, 10Mb (i.e., 4 VGA frames at 8-bit color) could fit easily within only a quarter of the budgeted area.

The key to our proposed approach runs counter to traditional high-performance data processing approaches: we propose the use of extremely-low voltage operation for ultra-power efficient operation. Traditional data processing elements run at maximum voltage or near maximum voltage (1.2V to 0.8V) to obtain high performance operation. While operation in this voltage range simplifies the task of meeting performance needs and is compatible with current design practices, it is inherently energy inefficient since a large amount of charge is stored on each of the signal wires. While reduced voltage operation has been proposed and used in the past, such voltage scaling has always been highly limited due to circuit design issues, particularly pertaining to memory cell stability and voltage level conversion. However, our recent research has demonstrated that it is possible to design data processing elements that are capable of operation as low as 200mV and below with full functionality.[18]

Figure 11 shows the energy per operation of a small processing element with supply voltage scaling down to 250mV and demonstrates as much as 20× energy efficiency improvement over traditional operation at full voltage. Hence, even this preliminary design shows that dramatic gains can be made in energy efficiency using ultra-low voltage operation while we expect to improve significantly on this result under the proposed research. If the supply voltage can be reduced to 200mV, energy efficiency can increase by as much as 30-40×, due to the quadratic dependence of energy on voltage. On the other hand, if we can successfully operate at 100mV, energy efficiency will improve by over two orders of magnitude, showing the potential of ultra-low voltage operation.

To counter low-voltage performance loss, and subsequently increase computational performance to the GOPS range, we propose the following approaches:

• Extensive pipelining and parallelism. We envision using hundreds of small simple, highly pipelined processing elements operating at ultra-low voltage.

• Adaptive Body Biasing (ABB) allows us to reduce V_{th}. Since performance is exponentially dependent on V_{th}, significant performance can be recovered.

• Small fast "shield" caches: designed for high-speed, low voltage operation in combination with larger, low-leakage caches operating at higher voltage with increased V_t using ABB. This simultaneously addresses the area overhead associated with low voltage caches and their performance loss while maintaining their energy efficiency.

Process-related variability has been identified as a significant problem that will only worsen as device dimensions scale downward. In,[19] it was shown that in subthreshold operation, random dopant fluctuation (RDF) effects dominate L_{eff} variation due to the diminishing impact of drain-induced barrier lowering (DIBL). This analysis ignored systematic V_{th} variability, however, and we intend to further investigate that important source of variability in low-V_{dd} circuits as part of the proposed work. One approach is to target differential circuit families that are less sensitive to global or systematic variability. Secondly, since RDF is local and independent in nature, the relative variability ($3\sigma/\mu$) reduces as multiple individual sources are summed together. This can be exploited by employing architectures and circuit topologies with deeper logic paths; however this runs counter to the approach proposed above to obtain high-throughput in the subthreshold regime. We will carefully weigh the resulting tradeoff between improved robustness in large logic depth circuits versus high throughput of heavily pipelined systems. We expect that by slightly increasing energy consumption under nominal conditions, it will be possible to significantly reduce variability and thereby improve energy efficiency across the expected process spread.

We propose the use of *soft-edge flip-flops* - these elements employ short periods of transparency by delaying the master clock while not adjusting the slave clock. This enables time borrowing, which also enhances averaging effects. This phenomenon is advantageous from a timing (or parametric) yield perspective. In a well-balanced sequential circuit where a critical stage may be followed by another critical stage, the D-Q delay of the first flip-flop might be increased due to slow silicon in the first logic stage which then causes timing failure in the subsequent critical path. However, replacing the FF between such critical paths by a soft-edge FF ensures that the second stage critical path does not fail.

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