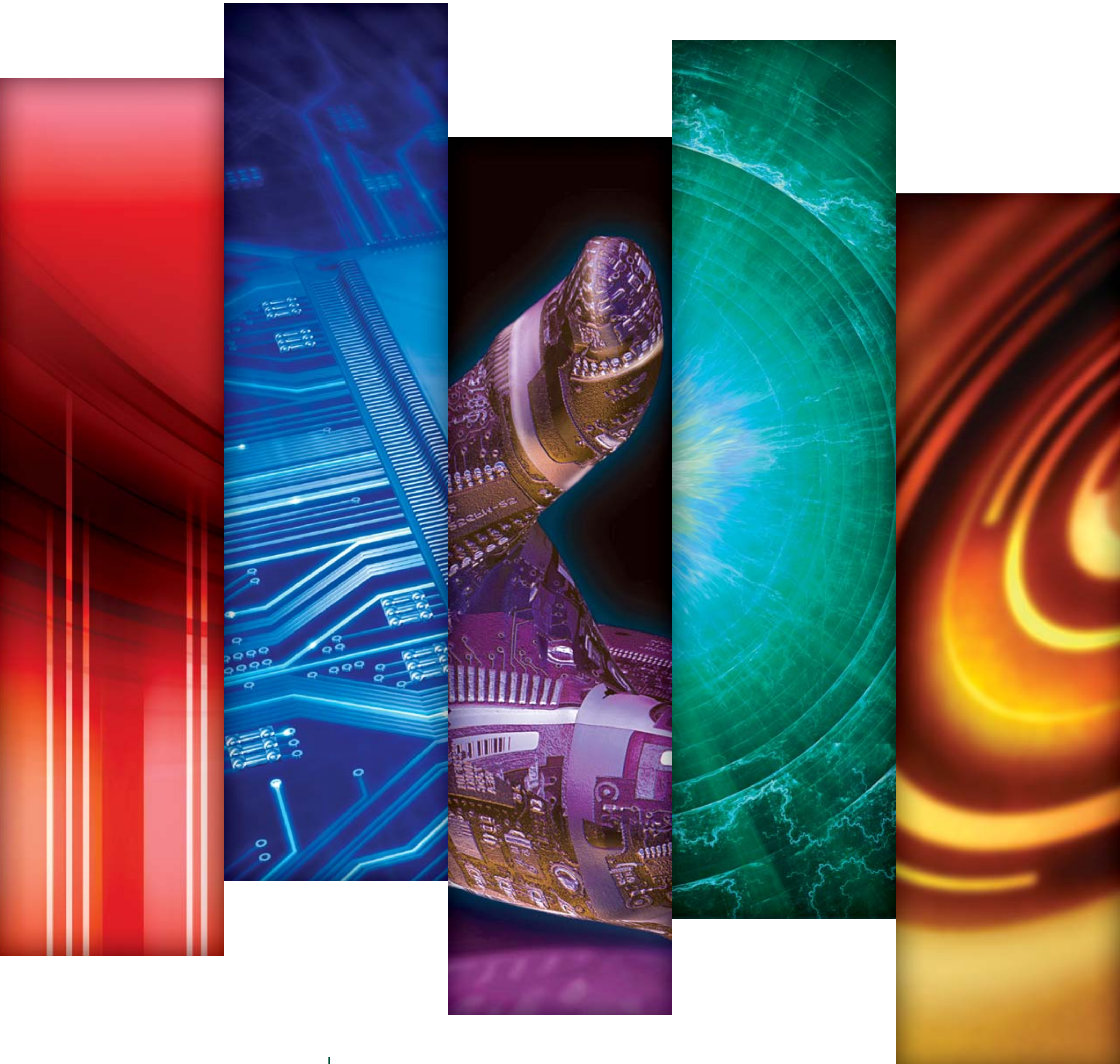
ELECTRICAL & COMPUTER ENGINEERING

2014 Research Highlights



MICHIGAN STATE UNIVERSITY | COLLEGE OF ENGINEERING

from the **Department Chair**

I am pleased to present a sampling of the research activities in the Department of Electrical and Computer Engineering (ECE). Electrical engineering and computer engineering have come to encompass many areas of investigation important to society including health, energy, transportation, security, and communication. The work displayed in the pages that follow shows some of the many ways that ECE faculty at MSU are working on important societal issues.

Research in our department has grown significantly over the past decade in terms of the number of projects, variety of projects, number of faculty members, and number of graduate students. Equally important is the extensive collaborations that have formed and grown with colleagues in other departments and colleges at MSU and elsewhere. These collaborations include work with other departments in the College of Engineering, as well as collaborations with colleagues in College of Natural Science, College of Education, College of Social Science, College of Human Medicine, College of Veterinary Medicine, College of Agriculture and Natural Resources, College of Communication Arts and Sciences, and the Facility for Rare Isotope Beams (FRIB).

ECE Department faculty and graduate students have significant participation in two centers including the NSF Science and Technology Center called BEACON (A Center for the Study of Evolution in Action) and the Fraunhofer USA Center for Coatings and Laser Applications. The facilities for research in ECE are located in the Engineering Building and the Engineering Research Complex, both on campus. The research also utilizes other laboratories on campus including microscopy facilities, cleanroom facilities, and other central laboratories. MSU, the College of Engineering, and the ECE Department are all committed to providing high-quality laboratory and computing facilities for research endeavors.

As you view the sampling of research activities presented in this brochure, you will see that the faculty and students are doing both fundamental and applied work important for the global society. The graduates from the program are well prepared to make continuing contributions in the future.

Graduate studies and research opportunities are available in biomedical areas, advanced computer architectures and networks, advanced computational techniques, communications, controls, electromagnetics, electronic materials and devices, microsystems, motors and drives, embedded systems, nondestructive evaluation, plasma science and plasma processing, power electronics, power systems, robotics, signal processing, and more. This list is not stationary and it is continuously changing as ECE brings new innovations to societal challenges and opportunities.

We are pleased to share our research activities and we look forward to working with you.

Timothy Grotjohn
Chair and Professor

Department of Electrical & Computer Engineering

The Department of Electrical and Computer Engineering at Michigan State University has a vibrant research program. The current faculty count is 50, including five University Distinguished Professors and two Endowed Chairs.

FACULTY HONORS

The faculty have received numerous awards and honors, including:

- Two National Academy of Engineering members,
- Fourteen IEEE (Institute of Electrical and Electronics Engineers) Fellows, and
- Fifteen NSF CAREER Award recipients.

SCOPE & GROWTH

The ECE Department has grown over the past decade substantially in terms of both the size of its graduate program and its research activities. The department student numbers include 250 graduate students with 180 Ph.D. students and 70 M.S. students. Total research expenditures are roughly $15,000,000 per year. The faculty have published 120 journal papers and 280 conference papers in the year 2013. Our undergraduate student population is 450 Electrical Engineering majors and 250 Computer Engineering majors with undergraduate Computer Engineering major being jointly offered with the Computer Science and Engineering Department.

RESEARCH CENTERS

The ECE Department has participation in several major research centers including:

- BEACON: NSF Science and Technology Center for the Study of Evolution in Action
- Fraunhofer USA Center for Coatings and Laser Applications
- Center for Revolutionary Materials for Solid State Energy Conversion (Department of Energy)

MISSION & GOALS

The mission of the ECE Department is to provide undergraduate and graduate education that is characterized by quality, access, and relevance; and to develop distinctive research programs in Communications and Signal Processing; Computer Engineering; Control, Robotics, and Power; Electro-magnetics, Electronic Materials and Devices, MEMS, and Plasma Sciences—each with the promise of sustained excellence as measured in scholarship, external investment, reputation, and impact. In support of this mission the department has three goals:

- graduating an inclusive group of Electrical Engineering and Computer Engineering B.S. degree students who start successful careers in the global market or succeed at graduate school,
- graduating an inclusive group of PhD and MS graduate student who are mentored to become leaders in industry, government, and academia, and
- growing the size and stature of the research and graduate programs with a focus on areas of national and societal benefits.

PUBLISHER / FACULTY EDITOR: Subir Biswas, Professor and Associate Chair for Research, Electrical & Computer Engineering

LAYOUT / DESIGN: Charlie Sharp, Sharp Des!gns

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Index

COMMUNICATIONS AND SIGNAL PROCESSING

COMPUTER ENGINEERING

CONTROL, ROBOTICS, AND POWER

ELECTROMAGNETICS, ELECTRONIC MATERIALS & DEVICES, MEMS, AND PLASMA

RESEARCH CENTERS

Communications and Signal Processing

Signal and Image Processing Laboratory

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Research in the SIGIMPR Lab focuses on the development of signal processing solutions to problems in signal representation, detection and classification. Currently, our group focuses on two application areas.

The first area of interest is the study of functional brain networks from multichannel neurophysiological data such as the electroencephalogram (EEG). In order to quantify the connectivity between different neuronal oscillations, we have recently proposed a new measure of time-varying phase synchrony based on complex time-frequency analysis referred to as Reduced Interference Distribution Time-Frequency Phase Synchrony (RID-TFPS). Using this measure, we have quantified the pairwise connectivity between different neuronal sites and constructed a graphical representation of the functional brain network (Fig. 1). Adapting methods from graph theory, we have identified the 'hub' nodes in the network as well as the community structure of the brain networks. We have also introduced a new measure of causality to quantify the directionality of information flow between different neuronal regions, named the Directed Information (DI) measure. The proposed DI measure can quantify the dependency as well as the causality between different oscillations thus separating the indirect connections from direct ones. All of these methods have been applied to a study involving error-related negativity which is a negative potential following an error and is an index of cognitive control. Impaired cognitive control plays a role in schizophrenia, impulse control and anxiety disorders among other psychopathologies.

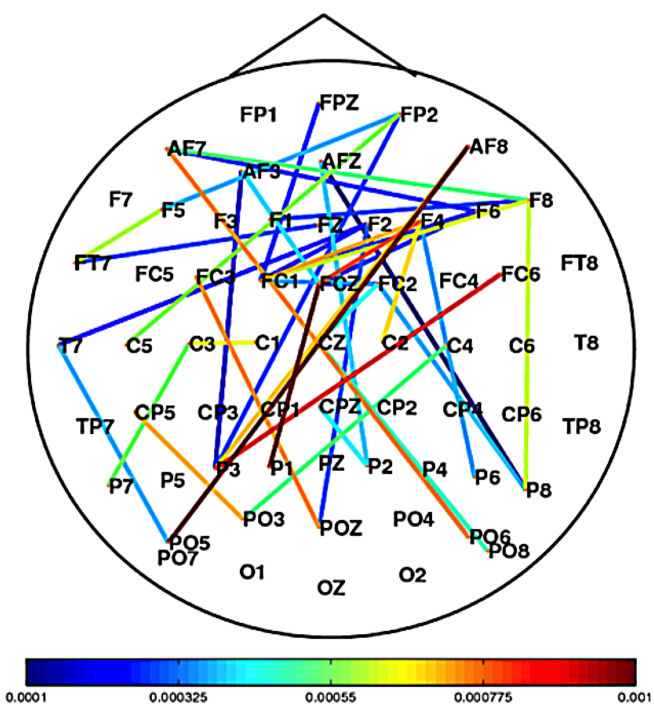

FIGURE 1. Significant functional connectivity map of the human brain during error-related negativity (ERN) quantified by RID-TFPS measure.

The second area of interest in our lab is the development of statistical learning algorithms for fault diagnosis and prognosis in electrical drives and machines in collaboration with Dr. Strangas and General Motors. In this area of work, we have combined statistical feature extraction algorithms with prediction methods such as Hidden Markov Models (HMM) and Extended Kalman Filtering (EKF) to determine the remaining useful life (RUL) of different components in electrical drives such as bearings. The goal of the proposed project is to develop reliable failure prognosis algorithms for critical electrical drive systems using minimal training and testing data and limited resources, i.e., small number of sensors and low computation power, and to apply these algorithms for accurate and timely failure mitigation of these systems to increase their reliability and performance.

ACKNOWLEDGEMENTS

Financial support for research in SIGIMPR was provided in part by Michigan State University, National Science Foundation (CCF-0746971, CCF-0728984, ECCS-1102316, CCF-1218377), Air Force Office of Scientific Research, General Motors, Siemens Corporation and Michigan Economic Development Corporation.

SELECTED RECENT PUBLICATIONS

E. Strangas, S. Aviyente, S. Zaidi and J. Neely, "The Effect of Failure Prognosis and Mitigation on Reliability of

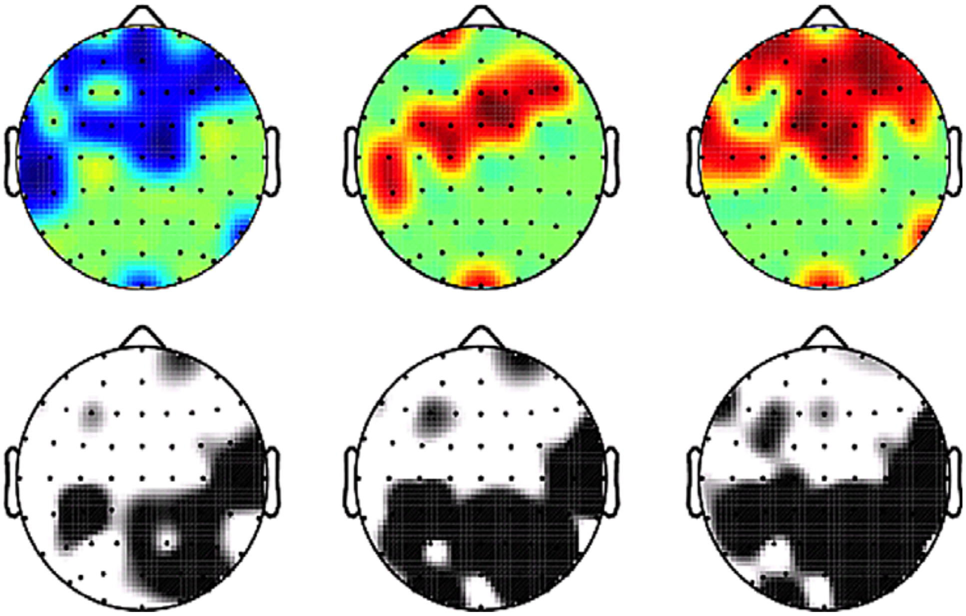

FIGURE 2. Error-correct difference for: path length (*left panel*), clustering coefficient (*middle panel*), and small-world parameter (*right panel*), significance $p < 0.01$

Permanent Magnet AC Motor Drives," *IEEE Transactions on Industrial Electronics*, in press.

M. Bolanos, E. M. Bernat, B. He and S. Aviyente," A Weighted Small World Network Measure for Assessing Functional Connectivity," *Journal of Neuroscience Methods*, vol. 212, no. 1, pp. 133–142, 2013.

J. Antonino-Davidu, S. Aviyente, E. G. Strangas and M. Riera, "Scale Invariant Feature Extraction Algorithm for the Automatic Diagnosis of Rotor Asymmetries in Induction Motors," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 100–108, 2013.

Y. Liu and S. Aviyente, "Quantification of Effective Connectivity in the Brain Using a Measure of Directed Information," *Computational and Mathematical Methods in Medicine*, special issue on Methodological Advances in Brain Connectivity, Article ID 635103, 2012.

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S. Aviyente, E. M. Bernat, W. S. Evans and S. R. Sponheim, "A phase synchrony measure for quantifying dynamic functional integration in the brain," *Human Brain Mapping*, vol. 32, no. 1, pp. 80–93, January 2011.

GROUP MEMBERS

Arash Mahyari, Rodney Singleton

Statistical Signal Processing Laboratory

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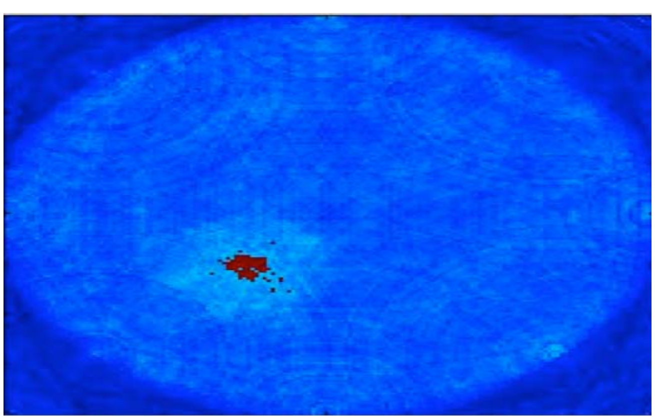
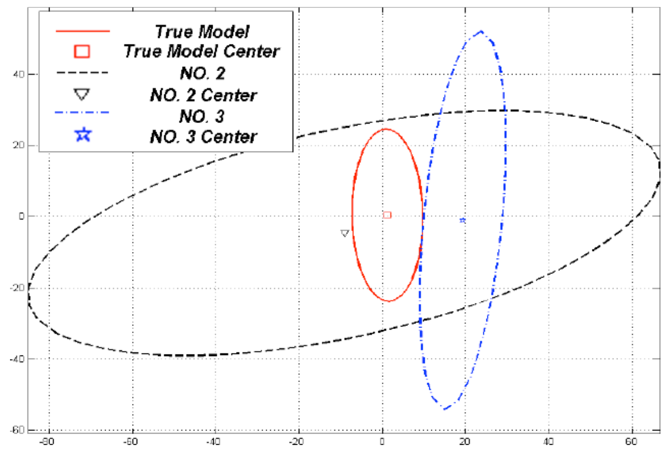
Researchers in the Statistical Signal Processing (SSP) Laboratory work at the interface between the classic mathematical fields of estimation, detection, and statistical modeling, and the rapidly changing contemporary advances in signal processing and computing. Below is a sampling of current activity motivated by and array of challenging problems in medicine, genomics, speech and image processing, and data security.

Breast Cancer Detection via Microwave Scanning and Evolutionary Computation

In collaboration with The NSF BEACON Center for Evolution in Action at MSU and researchers at East China Normal University in Shanghai, the SSP Lab is involved in avant garde research to use ultrawideband, extremely low power microwave imaging for screening of breast cancer. Development of this technology would be revolutionary in its implications for patient comfort and safety. The blue image below represents reconstructed and enhanced scan data from a patient with a cancerous tumor in the marked region. The pathology was later confirmed by surgery. The modeling of these images presents extreme challenges in automated interpretation and detection because of the very low signal power and high levels of noise and reflective interference. The image above is a representation of research into novel techniques for nonlinear modeling of low SNR data based on an innovative application of genetic algorithms and set-theoretic signal processing. Shown are three "families" of "chromosomes" that have exhibited survival potential in an "evolutionary competition" to represent the data.



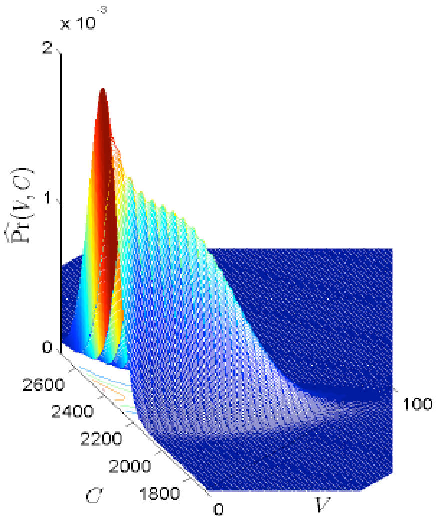


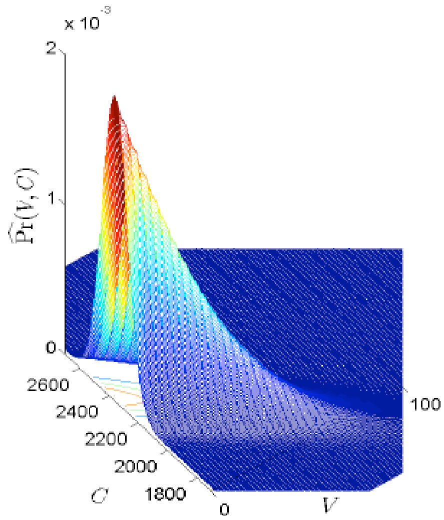
Bioinformatics: Determining Differential Expression of Genes

What genes and their mutations ultimately lead to the development of cancer? SSP researchers collaborate with MSU's internationally renowned Carcinogenesis Laboratory in seeking answers to this question. On the folowing page are distributions of features representing "gene expression" data. These findings suggest that current statistical models are adequate for interpreting differential effects of genes in differing conditions (e.g., treatment vs. control).

Image Fusion: Multiframe Super-resolution Based on New Developments in Matrix Completion

Multiple records of the same scene can be very useful in providing higher-quality images or more informative images for detecting important information. Combing multiple scenes can be difficult and counterproductive if the techniques used to not properly account for variations in illumination, differences in focus angle, and lost and distorted picture components. Researchers in the SSP Lab are investigating the application of new mathematical results recently developed for "compressive sensing" technologies to the problems of multiimage fusion. At the right are two "fused" results of right-focused

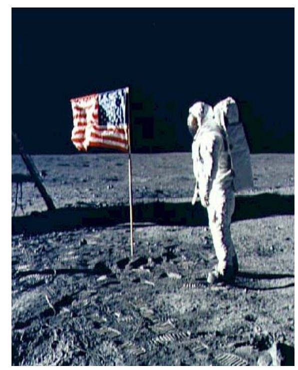




and left-focused images of Chicago's Water Tower Place. The top image is the result of employing current state-of-the-art fusion methods. The lower image was produced by new fusion methods developed by SSP Lab investigators in collaboration with colleagues at Beijing University of Technology.

Speech Processing: Secure Data Transmission and Storage

As an outgrowth and continuation of a recently completed NSF Digital Libraries project, SSP Lab researchers continue to investigate digital "watermarking" strategies for secure transmission and copyright protection of speech and image data. A technique known as parametric embedding can be used to deconstruct a speech or image frame, make imperceptible changes to the media model, then reconstruct the original material. This technique was developed as a copyright protection measure for the "National Gallery of the Spoken Word" which is hosted on the MSU campus, example material from which is illustrated below.



"I have a dream . . .," "One small step for man . . .," "Ich bin ein Berliner," "A date which will live in infamy . . ."

COLLABORATORS

BEACON Center for the Study of Evolution in Action, MSU (Prof. Erik Goodman, Dr. David Knuester)
East China Normal University, Shanghai (Prof. Yao Meng
Beijing University of Technology (Prof. Wang Zhuozheng)
Zhejiang University, Hangzhou (Prof. Wang Huiyan)
Michigan State University (Profs. Hayder Radha, J. Justin McCormick)

CURRENT GRADUATE STUDENTS

Blair Fleet, Yan Jinyao (PhD candidates)

VISITING FACULTY SCHOLARS

Prof. Wang Zhuozheng, Prof. Dou Huijing (Beijing University of Technology)

Broadband Access Wireless Communications Laboratory

Tongtong Li | ***tongli@egr.msu.edu*** | ***www.egr.msu.edu/bawc/***

Research at the Broadband Access Wireless Communication (BAWC) Lab at MSU is rooted in signal processing and wireless communications, and expands interactively to wireless security, ad-hoc and sensor networks, and interoperable wireless networks, with emphases on power and spectral efficiency, security and interoperability. The BAWC Lab has both software and hardware platforms for wireless communication system design, implementation and networking.

Secure and Efficient Wireless Communications

Security has become an urgent issue and a great concern in both civilian and military wireless communications. While people are relying more and more on wireless networks for critical information transmission, the ubiquitous wireless interconnectivity has also provided a primary conduit for malicious agents to exploit vulnerabilities on a widespread basis. Driven by the ever-increasing demand on secure wireless networking, development of novel wireless systems with built-in security has turned out to be the next impetus in communications.

How to strengthen wireless security and provide an ideal platform for promising wireless services such as mobile Internet and e-commerce? Patching or add-on security may be effective in the short run, but is far from adequate for addressing the needs on wireless security and can greatly complicate the communication systems. As pointed out by the President's Information Technology Advisory Committee: "We urgently need to expand our focus on short-term patching to also include longer-term development of new methods for designing and engineering secure systems."

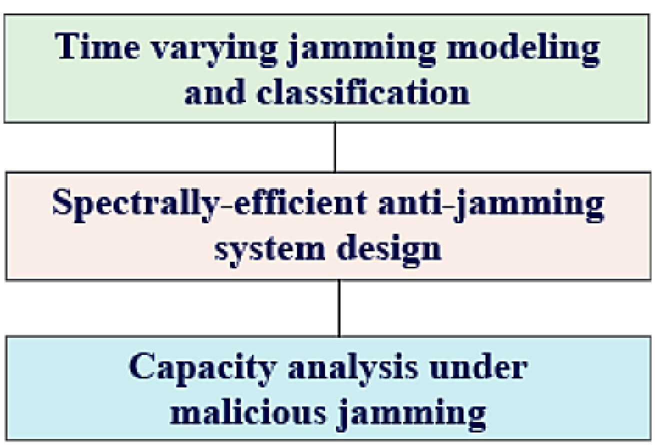


FIGURE 1. Recent workflow

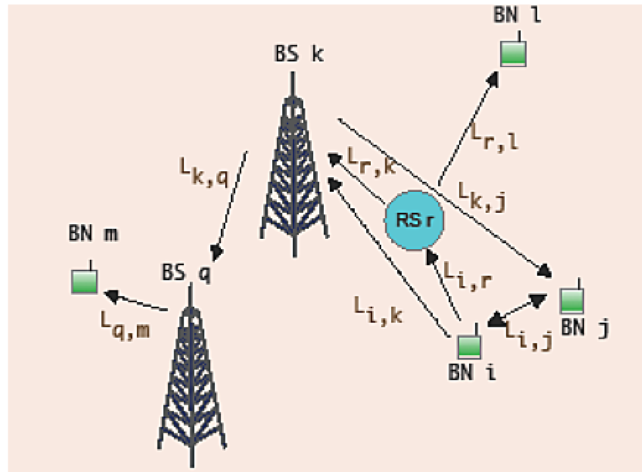


FIGURE 2. General wireless architecture design

This research is devoted to the fundamental study of new wireless security models and methods, and to design minimally intrusive wireless systems with built-in security. Our approach is to integrate advanced cryptographic techniques into the design of wireless systems and protocols. Our recent workflow on jamming modeling, anti-jamming system design and analysis is shown in Figure 1. We also study general network architecture design for more efficient, secure and timely information exchange, as shown in Figure 2.

Security in Wireless Sensor Networks

Due to significant resource limitation and lack of fixed structure, wireless sensor networks face even more serious security challenges than centralized networks. Recently, we have been work on reliable data fusion under malicious attacks, especially the Byzantine attacks, where the adversary has full control over some of the

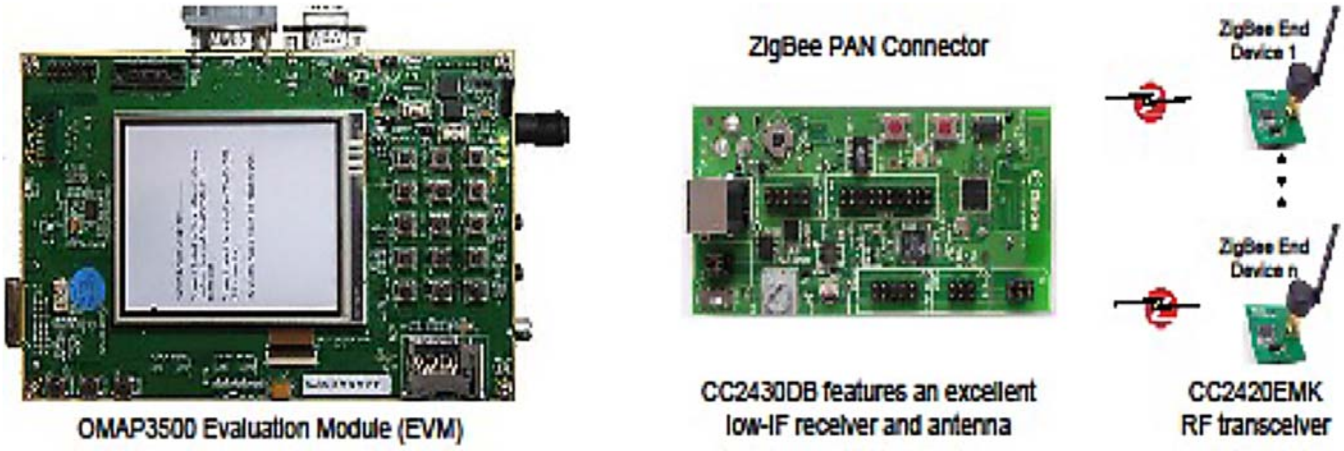


FIGURE 3. Prototyping of the secure access gateway

authenticated nodes and can perform arbitrary behavior to disrupt the system. Our analysis reveals an interesting and important result: in SENMA (sensor network with mobile access), even if the percentage of malicious nodes remains unchanged, larger size networks are much more reliable under malicious attacks. We are exploring resilient, scalable and energy efficient architecture design for wireless sensor networks. Effective network capacity and security will be investigated through a cross-layer perspective and collaboration among nodes from different layers.

Secure Communication and Control Systems for Smart Home and Smart Grid (in collaboration with the Cyber Security Lab)

Today, long-distance information exchange through wide area networks (WANs) has mainly been limited to phone-to-phone or phone-to-computer communications. At the same time, the development of human-to-device interfaces, such as home automation systems and integrated car-driver interfaces, has largely been limited to local area networks (LANs). The separation of WANs and LANs leads to an inconvenient gap in long distance control for general devices, especially moving devices, such as in-car electronics. In this research, we aim to develop cyber-enabled systems that can achieve seamless, secure monitoring and control of localized devices or device networks with a mobile phone. While providing a new class of wireless services, cyber-enabled device monitoring and control also imposes significant capacity and security/reliability demands on wireless networks, which have a limited spectrum and no protective physical boundary.

In this collaborative research, the BAWC Lab and the Cyber Security Lab aim to address the security and capacity requests raised in cyber-enabled, secure, remote monitoring and control, and accomplish a friendly human-device interaction platform by conjoining the communication capability and computational resources of the ubiquitous wireless networks with general physical components and devices.

ACKNOWLEDGEMENT

Our research is supported by National Science Foundation under multiple awards.

RECENT PUBLICATIONS

Lei Zhang, Huahui Wang and Tongtong Li, "Anti-Jamming Message-Driven Frequency Hopping: Part I-System Design," *IEEE Transactions on Wireless Communications*, ol. 12, No. 1, 2013, pp. 70–79.

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Tongtong Li, Jian Ren and Xiaochen Tang, "Secure Monitoring and Control Systems for Smart Home," *IEEE Wireless Communications*, Vol. 19, No. 3, 2012, pp. 66–73.

Lei Zhang, Jian Ren and Tongtong Li, "Time-Varying Jamming Modeling and Classification," *IEEE Transactions on Signal Processing*, Vol. 60, No. 7, 2012, pp. 3902–3907.

GRADUATE STUDENTS

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Biomedical Ultrasonics and Electromagnetics Laboratory

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Current research projects in the Biomedical Ultrasonics and Electromagnetics Laboratory primarily involve numerical modeling, fabrication, and evaluation of medical ultrasound probes for therapeutic and diagnostic applications. A significant portion of this research effort is involved in the design and implementation of rapid and accurate numerical models for thermal therapy and B-mode ultrasound imaging as well as the formulation of new analytical models for transient attenuation in human tissue based on fractional calculus. Additional ongoing efforts are concerned with the fabrication of new ultrasound phased array devices for therapeutic applications and methods to integrate these devices with ultrasound imaging probes to provide real-time image guidance during these procedures.

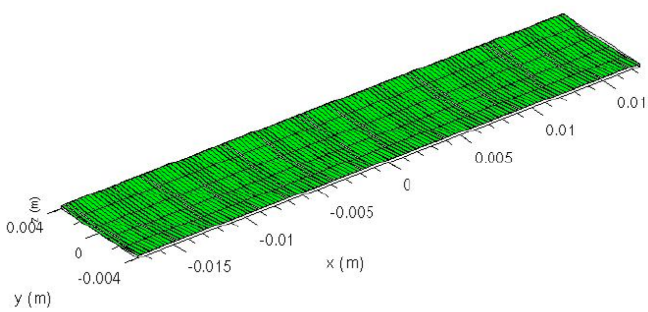

FIGURE 1. Geometry of a simulated 128-element linear array in FOCUS.

Numerical Modeling of Medical Ultrasound

The FOCUS software package was created in the Biomedical Ultrasonics and Electromagnetics Laboratory at Michigan State University to facilitate rapid, accurate, and memory-efficient simulations of biomedical ultrasound. FOCUS, which is the 'Fast Object-oriented C++ Ultrasound Simulator,' is free software that runs in Matlab. FOCUS models linear transient and continuous wave pressures generated by single transducers and ultrasound phased arrays. FOCUS also supports nonlinear transient calculations for circular and spherically focused transducers. Although the programs in FOCUS are primarily intended to model therapeutic and diagnostic ultrasound, FOCUS provides a set of flexible routines that are readily adapted to several different applications. New routines that exploit the latest algorithms and computer technology are under continuous development for FOCUS.

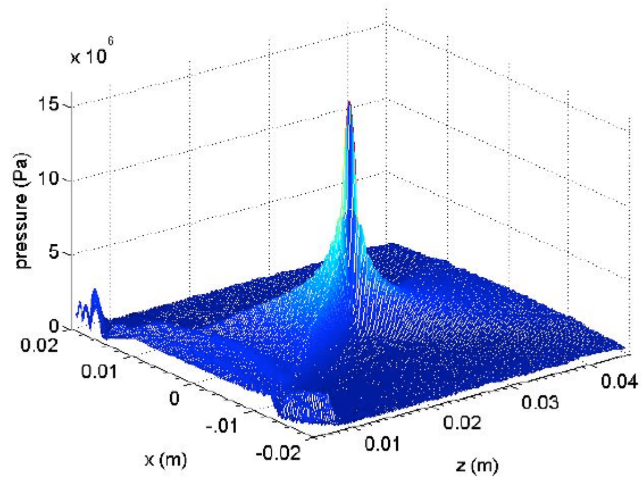

FIGURE 2. Pressure calculated by FOCUS in the *xz* plane at *y* = 0mm. The array in Figure 1 is electronically focused at *z* = 25mm.

Radiation Force Calculations

The array in Fig. 1 and simulated pressure in Fig. 2 are examples generated for radiation force calculations with a simulated Vermon L5 phased array imaging probe. The full 3D pressure simulations were completed in less than 3 minutes on a standard desktop computer.

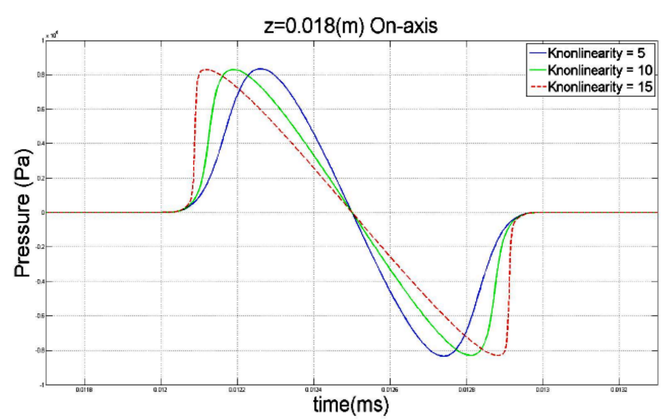

FIGURE 3. Simulated nonlinear propagation of ultrasound generated by a circular transducer.

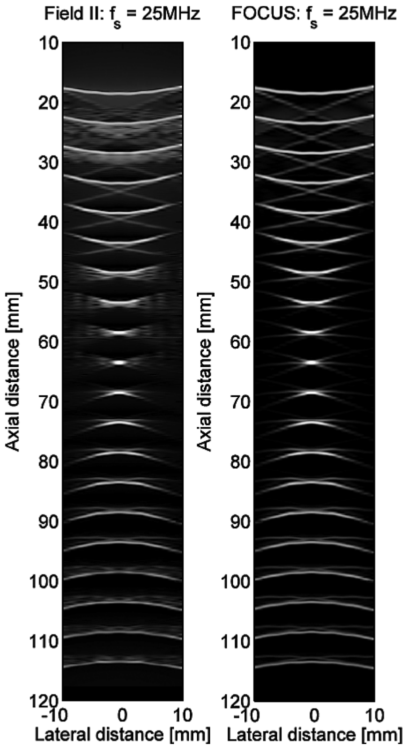

FIGURE 4. Simulated B-mode images generated by a linear ultrasound array.

Simulations of Nonlinear Ultrasound Propagation

Nonlinear simulation capabilities have recently been added to FOCUS. These nonlinear simulations evaluate the KZK equation for circular and spherically focused transducers using an implicit finite difference method. Examples of nonlinear ultrasound pulses generated by a circular transducer for different values of the nonlinearity parameter are shown in Fig. 3.

B-mode imaging simulations

Novel diagnostic ultrasound algorithms, advanced beamformers, and signal and image processing methods are frequently evaluated with computer simulations. Despite recent improvements in computer speed, ultrasound simulations of more than a few frames remain computationally intensive. The need for faster, more accurate, and more memory-efficient simulations of ultrasound imaging motivates the development of new software tools for these calculations in FOCUS. An example of an ultrasound image simulated in FOCUS is shown on the right hand side of Fig. 4, which shows that image simulations in FOCUS also achieve reduced nearfield clutter.

Fractional Calculus Models of Ultrasound Attenuation in Biological Media

To support efforts to simulate transient ultrasound propagation in lossy media, we are developing theoretical and numerical models based on fractional calculus. These fractional calculus models are ultimately intended for linear B-mode imaging and for nonlinear ultrasound propagation.

SUPPORT

This research is supported in part by NIH Grant R01 EB012079.

RECENT PUBLICATIONS

F. Liu, M. M. Meerschaert, **R. J. McGough**, P. Zhuang, and Q. Liu, "Numerical methods for solving the multi-term time-fractional wave-diffusion equation," *Fractional Calculus and Applied Analysis*, vol. 16, no. 1, pp. 9-–25, 2013.

P. Straka, M. M. Meerschaert, R. J. McGough, and Y. Zhou, "Fractional wave equations with attenuation," *Fractional Calculus and Applied Analysis*, vol. 16, no. 1, pp. 262–272, 2013.

E. J. Alles, Y. Zhu, K. W. A. van Dongen, and R. J. McGough, "Rapid Transient Pressure Field Computations In The Nearfield Using Frequency Domain Time-Space Decomposition For Circular Transducers," *Ultrasonic Imaging*, vol. 34, no. 4, pp. 237–260, 2012.

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GRADUATE STUDENTS

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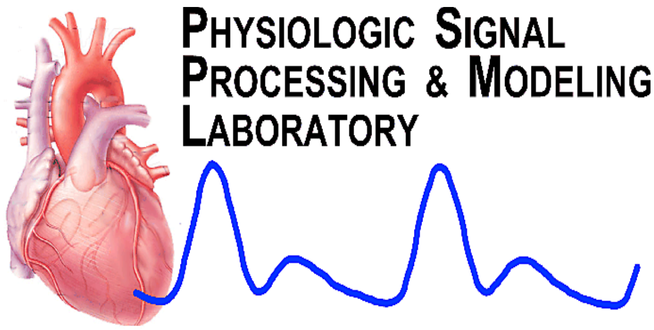

Our broad research aim is to decipher the "hidden" information in biomedical measurements through signal processing and modeling in order to advance the basic understanding of physiology and establish improved patient monitoring systems. Our current focus is to develop and experimentally validate innovative physiology-based signal processing techniques for hemodynamic (circulatory) monitoring and probing neural cardiovascular regulation.

Hemodynamic Monitoring

Signal processing and modeling represent a potential, practical approach for achieving sorely needed reliable, automated, and less invasive monitoring of hemodynamics. As a result, investigation of this approach has been longstanding. However, the previous techniques have neglected key aspects of the physiology and are therefore only able to monitor a limited number of variables that show accuracy over a narrow hemodynamic range. We have developed a suite of signal processing techniques that account for the crucial facets of the physiology omitted hitherto via diverse (black-box to physical) models to estimate various essential hemodynamic variables (e.g., cardiac output, left atrial pressure, ejection fraction) from more readily available blood pressure signals. We have demonstrated the validity of these techniques against manual or more invasive reference measurements from experimental subjects and patients during wide hemodynamic perturbations. Several of these techniques have been licensed to Retia Medical, LLC. Our focus now is to improve the measurement of blood pressure itself. We are attempting to improve the accuracy of automated arm blood pressure cuff systems, which are notoriously unreliable, based on physical modeling of oscillometry. We are also seeking to achieve cuff-less blood pressure monitoring based on unique estimates of pulse wave velocity. This latter research could potentially lead to improved hemorrhage detection of our warfighters.

Probing Neural Cardiovascular Regulation

Neural cardiovascular regulation maintains blood pressures by multiple, fast feedback control mechanisms so as to protect blood flow to the brain, heart, and other vital organs during activities such as exercise and postural changes. This regulatory process is disturbed in various disease processes such as diabetes and heart failure. It is therefore important to be able to quantitatively probe neural cardiovascular regulation. Signal processing of beat-to-beat cardio-respiratory fluctuations is a unique approach for being able to reveal the important dynamic properties of specific neural cardiovascular regulatory mechanisms during normal physiologic conditions. Although power spectral analysis of resting heart rate variability has been the workhorse in the area, such a single signal analysis technique only characterizes an output response of the regulatory system rather than the system itself. To overcome this limitation, a number of multi-signal, system identification techniques have been developed. However, these techniques have largely focused on the neural control of heart rate. We have developed a set of system identification techniques for characterizing the control of other important variables as well as for overcoming limitations of heart rate power spectral analysis. We have validated these techniques mainly using interventions of known effect in experimental subjects. While neural cardiovascular regulation has long been viewed as only a short-term mechanism, recent experimental studies have shown that it may have long-term impact and therefore play an important role in hypertension. Our goal now is to elucidate the long-term effect of neural cardiovascular regulatory mechanisms on blood pressure.

CURRENT LAB MEMBERS

GRADUATE STUDENTS: Mingwu Gao, Jiankun Liu, Mohsen Moslehpour, Guanqun Zhang. POST-DOC: Federico Aletti

COLLABORATORS

Victor Convertino (US Army), Jin-Oh Hahn (University of Maryland), Donal O'Leary (Wayne State University), Bari Olivier (MSU), Andrew Reisner (MGH)

RECENT PUBLICATIONS

Liu J, Hahn JO, Mukkamala R. "Error mechanisms of the oscillometric fixed-ratio blood pressure measurement method." *Annals of Biomedical Engineering*, 2012 Nov 21. [Epub ahead of print]

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Mukkamala R, Xu D. "Continuous and less invasive monitoring of central hemodynamics by blood pressure waveform analysis." *American Journal of Physiology*, 299(3):H584–H599, 2010.

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CURRENT SPONSORS

Michigan Universities Commercialization Initiative, NIH (AG041361), NSF (CAREER 0643477), Retia Medical, US Army (W81XWH-10-2-0124)

Neural Systems Engineering

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We're primarily interested in: (1) studying the basic mechanisms of sensorimotor integration and plasticity in the brain; (2) engineer clinically viable brain machine interface (BMI) systems to restore, augment or repair damaged neurological function such as hearing, sight and movement.

We focus on the mechanisms of neural integration and coordination in sensorimotor systems in rodents and nonhuman primates. In particular, we seek to understand: (1) how ensembles of neurons represent and integrate multiple sensory cues to guide motor action; (2) how neural computations take place at the cellular and population level with cell-type specificity; (3) how neural ensemble activity can be decoded to actuate artificial devices; (4) how precise control of cell-type-specific events can perturb and control neural responses to evoke desired behavioral outcome.

A Clinically Viable Brain Machine Interface

Brain Machine Interfaces (Fig. 1) have witnessed a revolutionary progress in the last few years, providing a proof of concept that brain signals can be effectively used to actuate paralyzed limbs or artificial neuroprosthetic devices, such as computer cursors or anthropomorphic robotic arms moving in 3D space. Their potential use in clinical applications, however, has been hindered by numerous challenges, ranging from diminished information yield over chronic use, to highly nonstationary and heterogeneous characteristics of neuronal activity patterns. For this technology to be clinically viable, it needs to address many of these challenges to pave the way for people with severe sensory, cognitive and motor deficits to significantly improve their lifestyles.

This project specifically addresses neural decoding—the problem of translating information in neural signals, collected at cellular and population levels, to control signals that actuate an artificial device. The objective is to provide the most effective means of controlling an 11 degree of freedom robotic arm and hand using a population of cortical neurons recorded through implanted microelectrode arrays in primary motor cortex areas of non-human primates. The outcome of these studies is expected to significantly improve the ability of neural decoders to generalize to novel tasks under a variety of contexts, and provide dexterous motor control of artificial limbs, such as reaching to grasp and manipulate external objects.

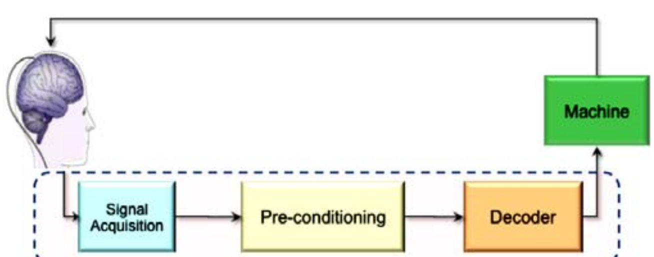

FIGURE 1. A Brain-machine interface.

Mining Large-Scale Neural Ensemble Recordings

This project seeks to improve our understanding the phenomenological aspects of neural plasticity that underlies our ability to learn, memorize or recover from injury. Specifically, we are interested in the neural mechanisms that underlie sensorimotor integration during associative and perceptual learning that guide motor behavior. These mechanisms are known to undergo significant changes during development, but more interestingly, during closed-loop brain machine interface experiments. We specifically focus on those mechanisms that can be assessed by analyzing the coordinated activity patterns of many, simultaneously observed, neurons.

A Wireless, Multiscale, Distributed Interface to the Cortex

High-density microelectrode arrays (MEAs) permit simultaneous recording of multiple single neurons that mediate sensory and motor processing, perception, and learning in the cerebral cortex. MEAs also have the potential to monitor functional alterations in neuronal circuits within awake, behaving subjects to better understand and quantify cortical plasticity. They can also serve in Brain Machine Interface (BMI) systems to provide real-time control of assistive devices in people with severe disability. The challenge in this project is the ability to extract the activity of many individual neurons and local field potentials (LFPs) within the constraints imposed by implantability requirements (such as chip size, power dissipation, real-time operation, and limited telemetry bandwidth), which signficantly limits the utility of MEAs in basic neuroscience and clinical applications.

The objective of this project is to develop a highly modular, ultra low-power and distributed microsystem to extract some important aspects of the neural code (such as neuronal spike times, firing rates and LFPs) from large populations of neurons wirelessly and in real-time. Some example applications of this system in basic and clinical neuroscience are: (1) Studies of neural coding and plasticity in freely behaving, untethered subjects interacting naturally with their surrounding. (2) Real time control of neuroprosthetic devices and Brain Machine Interfaces. (3) Prediction of impending chronic seizures in epileptic patients. (4) Closed loop feedback control for neuro-modulation and neurostimulation (e.g., deep brain stimulation of Parkinson's disease patients)

Computational and Experimental Techniques Regularly Used in the Lab

- **BEHAVIORAL:** We train rodents on sensorimotor integration tasks that require the animal to integrate multiple sensory cues over delay intervals to guide motor action for reward.
- **CELLULAR:** *In vitro:* We use patch clamp techniques in thalamocortical brain slices to characterize the postsynaptic events caused by the integration of thalamic synaptic afferents with motor intracortical inputs and their effects on the dynamics and plasticity of cortical states.

  In vivo: We use microelectrode arrays implanted in awake behaving animals to *simultaneously* monitor the extracellular activity of spiking neurons in brain areas of interest. Areas of interest are the medial Prefrontal Cortex, the primary somatosensory cortex, the thalamus and motor cortex. We use standard histological assessment (e.g., Nissl, cytochrome oxidase) to determine recording sites and immunohistochemistry to assess long-term effects of chronically implanted arrays.
- **MOLECULAR:** We use optogenetic manipulation of cell-type-specific events to perturb and control population responses. We sensitize neurons using viral transfection of Channel-rhodopsins and Halorhodospin to different colors of laser light. This permits highly selective activation/inactivation of specific cell types with millisecond precision. We examine how neuronal excitability can be controlled in this manner at the population and circuit levels to alter neural computations; thereby permitting to decipher complex brain circuits involved in perception/action or normal/diseased states.
- **ENGINEERING:** We engineer wireless, miniaturized electronic systems that can be chronically implanted in awake, freely behaving subjects' brains. These systems enable us to *continuously* monitor neural activity while subjects interact with their surrounding.
- **COMPUTATIONAL:** We develop signal processing algorithms for analyzing spiking patterns of many neurons. We develop mathematical models of neural encoding to characterize population responses to specific task events. We also develop graph-based neural decoding algorithms to control robotic arms during reach-to-grasp tasks.

RECENT PUBLICATIONS

J. Daly, J. Liu, M. Aghagolzadeh, K. Oweiss (2012) "Optimal Space Time Precoding of Artificial Sensory Feedback through Mutichannel Microstimulation in Bi-directional Brain Machine Interfaces," *J. of Neural Engineering*,

S. Eldawlatly, K. Oweiss (2011) "Millisecond-Timescale Local Network Coding in the Rat Primary Somatosensory Cortex," *PLoS ONE*

J. Liu, H. Khalil, K. Oweiss (2011) "Neural Feedback for Instantaneous Spatiotemporal Modulation of Afferent Pathways in Bi-directional Brain Machine Interfaces," *IEEE Transactions on Neural Systems & Rehabilitation Engineering,* 19:5, pp 521–533

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S. Eldawlatly, R. Jin, and K. Oweiss, (2009) "Identifying Functional Connectivity in Large Scale Neural Ensemble Recordings: A Multiscale Data Mining Approach," *Journal of Neural Computation*, MIT Press, 21:2, pp. 450–477

GROUP MEMBERS

POSTDOCS: Erin Purcell, PhD, Shiying Hao, PhD. PHD STUDENTS: John Daly, Ali Mohebi, Farzad Asgarian, Ahmed Eleryan, Islam Badreldin, Mehrdad Hashemi, Wilfredo Cartagena, Andy Tomaswick, May Mansy. UNDEGRADUATES: Hannah Batchelor, Samuel Akwei-Sekyere, Marissa Zoratti. TECHNICIAN: Cindy Knaff

SPONSORS

Defense Advanced Research Project Agency, National Institute of Neurological Disorders and Stroke

The WAVES Laboratory

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The WAVES Lab focuses on the theory and application of multidimensional signal processing, information-theory, and related statistical analysis areas, which are rooted in machine learning and data mining, to address problems in different application areas. Application areas that are being investigated by the WAVES Lab include imaging, social networks, sustainability, visual communications, and wireless networks.

Data Recovery by Signal Sparsificiation

The WAVES Lab is developing new approaches for the recovery of missing data and lost information using the principle of signal sparsification, which includes compressed sensing and rank minimization. This research, funded by NSF, is enabling novel algorithms for image demosaicking (recovery of missing colors), deblurring, denoising, super-resolution, and visual coding.

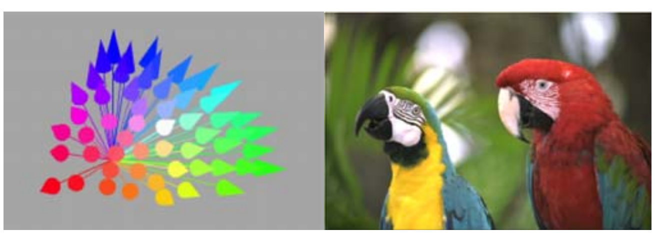

FIGURE 1. Utility of novel color frames (*left*) for the recovery of missing colors in images (*right*). This principle can be applied to a broad range of applications for the recovery of missing information or data.

New direction is being explored in the recovery of critical information embedded within massive amount of data and the reconstruction of high-resolution environmental data-fields from limited samples captured by sensor networks. This includes the application of more general principles of sparse coding for the recovery of multi-dimensional data fields. In particular, we are employing signal sparsification and rank-minimization principles for the recovery and reconstruction of high-resolution and high-dimension tensor data found in environmental modeling of a variety of data-fields. These data-fields could represent any physical or biological parameters that scientists and environmentalists are interested in.

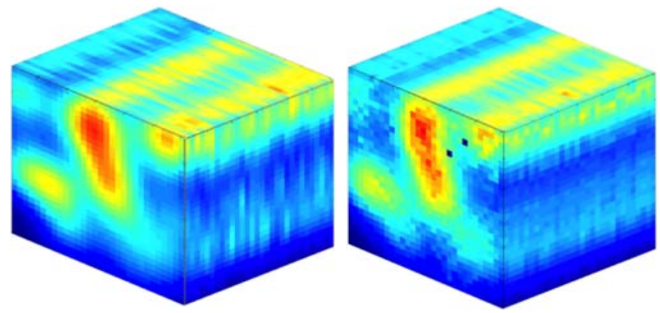

FIGURE 2. An example of a three-dimensional tensor field (*left*) representing a Gaussian-mixture model of a 3D parametric data (e.g., temperature of an aquatic surface that is changing over time). By applying principles of signal sparsification, a reconstruction (*right*) of the original field can be achieved using a small number of available samples (e.g., 10–20%) of the original field.

Analysis of Social Networks

In collaboration with other research groups, the WAVES Lab is pursuing new research directions for the analysis of on-line social networks and their underlying infrastructure

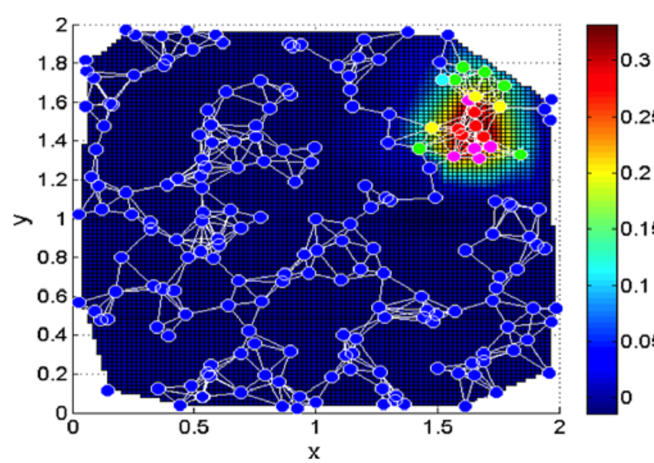

FIGURE 3. Detection of influential nodes, information hubs, and communities in social networks.

and services. We are developing new graph transforms, signal processing, information-theoretic, and machine learning tools for the analysis and understanding of massive social network graphs and services.

A core component of this NSF funded multi-disciplinary research is close interaction with social scientists and other experts in related fields. In that context, we are addressing fundamental and emerging questions in the analysis of social networks. This includes the detection of communities, the identification of influential nodes and information hubs, performing transitivity analysis of social network graphs, and denoising massive social network graphs using novel signal processing transforms and related tools from information theory and machine learning.

Visual Retargeting and Summarization

New approaches for content-aware visual "retargeting" are being developed. A variety of display devices that prohibit maintaining the original aspect ratio of the captured visual content are considered. Multi-resolution approaches that are robust to a variety of visual content distortion are being designed and analyzed. Extensions of these approaches to 3D visuals and displays are being investigated.

FIGURE 4. Visual retargeting using multi-resolution analysis.

Novel video summarization frameworks are being explored. This includes new algorithms for the extraction of key frames from consumer videos and the construction of "informative" video-summary excerpts from long video sequences.

Reliable and Stable Wireless Multimedia

Reliable efficient and stable wireless link-layer protocols are being designed, analyzed and implemented for high-end emerging multimedia applications over wireless networks. These protocols provide joint reliability and stability for both delay constrained real-time video applications and traditional applications that are built on TCP/IP. Target applications include multimedia streaming, telemedicine/health monitoring, surveillance, and gaming.

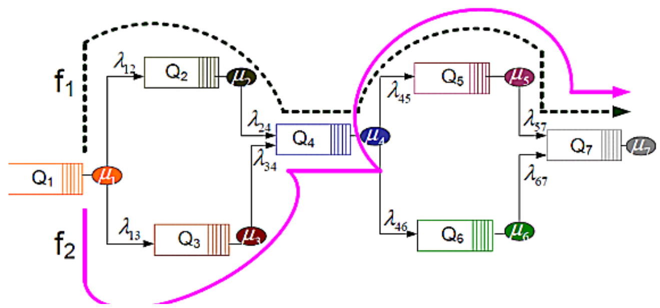

FIGURE 5. Reliable and stable protocols for wireless multimedia.

Network Coding and Network Channel Coding

Migrating coding functions from end nodes into intermediate nodes within the network represent a major paradigm shift with improvements in throughput, delay, and/or reliability. Based on support from two NSF grants, the WAVES lab has developed advanced network-embedded source and channel coding approaches over network topologies that are representatives of next generation Internet and wireless networks, sensor networks, peer-to-peer networks, and ad-hoc networks.

Nondestructive Evaluation Laboratory

Lalita Udpa | ***udpal@egr.msu.edu*** | ***researchgroups.msu.edu/ndel***

The Nondestructive Evaluation (NDE) laboratory focuses on design and development of sensors and systems for monitoring and evaluating structural integrity of parts and components. The varied nature of materials to be inspected have led to the need for new low cost sensors with high sensitivity to detect flaws buried deep in materials before they reach critical dimensions. The NDEL group works on electromagnetic (magnetic flux, eddy current, microwave methods), Ultrasonic (Lamb wave, acoustic), x-ray, IR thermography and optical and electromagneto-acoustic (EMAT) sensors. NDE is a multi-disciplinary field and comprise three major research activities; (1) computational modeling, (2) inverse problem solution and (3) sensor system design

This work is done in close collaboration with Satish Udpa (ECE) and Mahmood Haq (ME).

Steam generator (SG) tubes in nuclear power plants are continuously exposed to harsh environmental conditions including high temperatures, pressures, fluid flow rates and material interactions resulting in various types of degradation mechanisms such as mechanical wear, stress corrosion cracking (SCC), pitting, and inter granular attack.

NDEL has developed a simulation model having capability to predict eddy current signals from realistic SG tube and defect geometry.The model helps visualize field/flaw interactions and thereby optimize probe designs and inspection parameters (see Fig. 1). The model is used by industry as a test bed for studying signal formation that can be used in training pattern classification algorithms used in automated signal analysis.

Screen shot of the data analysis software developed at MSU, to provide rapid, consistent, and accurate analysis of the field data collected during SG tubing inspection is shown in Fig. 2. This software is now deployed by industry for SG tube data analysis.

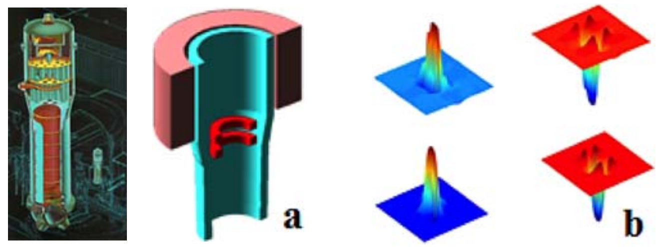

FIGURE 1. Steam Generator Tube Simulation GUI: (A) FE model mesh, (B) Validation of simulation (*top:* experiment, *bottom:* simulation).

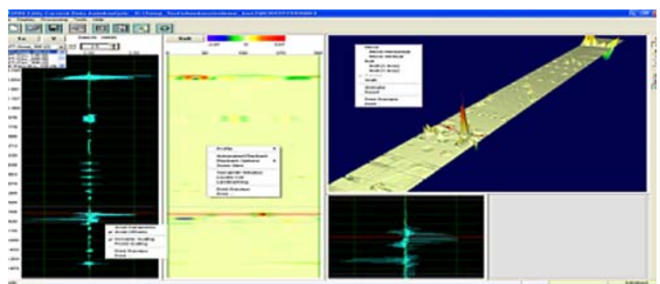

FIGURE 2. Auto-analysis software GUI

Wireless Sensor Networks (WSN) offer a promising solution for continuous Structural Health Monitoring of various industrial and civil structures. WSNs are inherently highly scalable and configurable and do not require high installation and maintenance cost.

As shown in Fig. 3 the proposed research aims to develop a wireless multi-modal sensor network system for actuation and sensing to enable real-time monitoring of structural health. The sensing modalities that will be investigated in this research include passive techniques such as acoustic emission (AE) and active Lamb wave techniques. The main appeal of these techniques is that these modalities can be implemented using inexpensive PZT patches, which are surface mounted on the structure to be monitored without interrupting the structure's operation.

NDEL students work on developing an interface between sensor nodes and PZT patches for data acquisition using the underlying inspection technique. The Sensor nodes are programmed with embedded distributed algorithms for detecting and characterizing defects.

IR Thermography and Optical techniques are utilized for temperature measurements that can be further used to detect subsurface defects, crack growth under static and dynamic loads in joints, welds, etc. *Thermoelastic stress analysis* (*TSA*) is an experimental technique based on thermoelastic effect that provides full-field stress maps from the surface of the specimen. Under adiabatic,

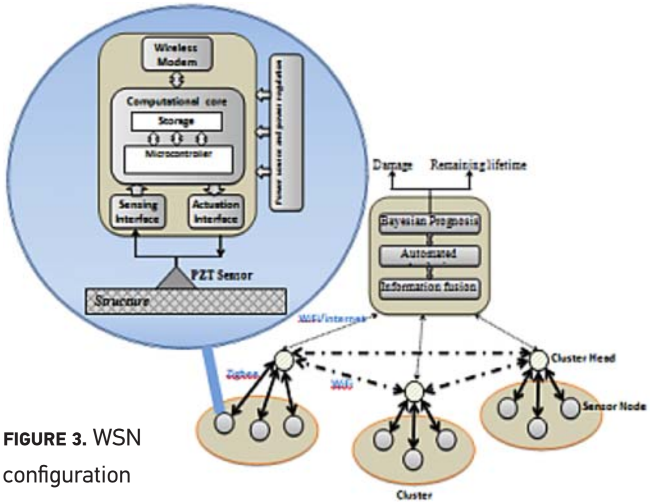

FIGURE 3. WSN configuration

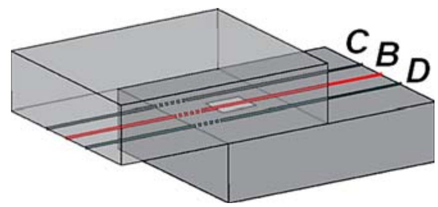

FIGURE 5. Single-lap adhesive joint with manufacturing defect and reference FBG sensors C and D and test FBG sensor B [7, 8]

conditions, a structural component subjected to cyclic load experiences small, reversible temperature changes which are proportional to the sum of principal stresses (Fig. 4).

TSA experiments provide information about crack face contact, or closure during the cyclic loading conditions. This can also provide vital information on extent and growth of rack/damage.

Fiber Bragg-grating (FBG) sensors are of great interest in aerospace, marine, and automotive applications due to many advantages including small physical size, ease of embedding in composite structures, immunity to electromagnetic interference and excellent multiplexing capabilities. FBGs are the only technique that can provide reliable information in bonded joints without affecting the intrinsic properties, or initiating damage in the bonded layer. Current work at NDEL focuses on developing robust and reliable technique capable of defect location and damage severity estimation by strategically placement of an array of embedded FBG sensors in the adhesive layer of the structural composite joints (Figure 5). Such technique provides vital information about the stresses in the adhesive layer and used to develop design tools based on the experimentally validated simulations (EVS).

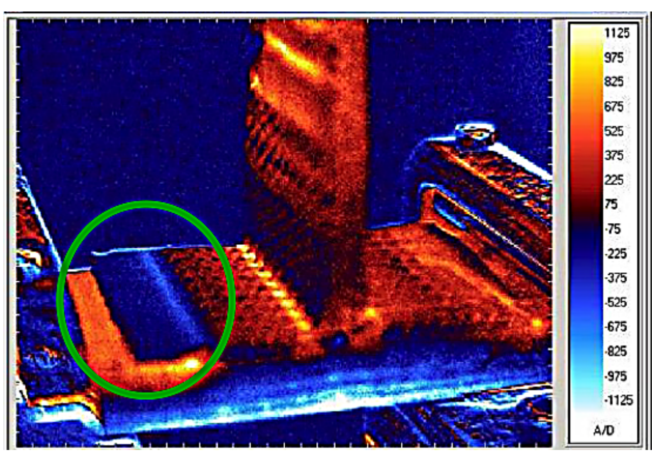

FIGURE 4. TSA used to study the defects and crack growth in Pi-/T-composite joints [6]

NDEL also works on *Interferometric techniques* including Optical Coherent Tomography and Holographic Interferometry (HI) on developing techniques that would characterize and locate flaws in thick, multilayered transparent structures. It should be noted that these techniques can be easily extended to biomedical applications and other disciplines.

GROUP MEMBERS

Satish Udpa (ECE), Mahmood Haq, Assistant Professor, Mechanical Engineering; Anton Khomenko, Research Associate; 12 PhD, MS, and undergraduate students

RECENT PUBLICATIONS

S. Majumdar, S. Ramakrishnan, P. Ramuhalli, L. Udpa, S. Udpa, J. Benson, R. Williams, T.U. Bipes. "Automated Data Analysis System for Steam Generator Tube Inspection," *Materials Evaluation*, Vol. 69(2), pp. 201–207, (2011).

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M. Haq, L. Drzal, E. Patterson, "Health Monitoring of Composite Pi-Joints Using Fiber Optic Sensors," American Society of Composites, 25th Annual Technical Conference, Dayton, Ohio, USA, September 2010.

M. Haq, A. Khomenko, L. Udpa, S. Udpa, "Fiber Bragg-Grating Array for Health Monitoring of Bonded Composite Lap-Joints," to be presented at SEM 2013 Annual Conference & Exposition on Experimental and Applied Mechanics, Chicago, IL, USA, 3–5 June, 2013.

Nondestructive Evaluation Laboratory

Satish Udpa | ***udpa@egr.msu.edu*** | ***researchgroups.msu.edu/ndel***

The Nondestructive Evaluation (NDE) laboratory focuses on design and development of sensors and systems for monitoring and evaluating structural integrity of parts and components. The varied nature of materials to be inspected have led to the need for new low-cost sensors with high sensitivity to detect flaws buried deep in materials before they reach critical dimensions. Some of the aging infrastructures in the nation range from fleet of aircrafts that fly beyond their design life, nuclear power plants, natural gas transmission pipelines, bridges, etc. The NDEL group works on electromagnetic (magnetic flux, eddy current, microwave methods), ultrasonic (Lamb wave, acoustic), x-ray, IR thermography and optical and electromagneto-acoustic (EMAT) sensors. This work is conducted collaboratively with Lalita Udpa (ECE) and Mahmood Haq (ME).

NDE is a multi-disciplinary field and comprise three major research activities; (1) computational modeling, (2) inverse problem solution and (3) sensor system design (see Figure 1).

Oil pipeline ruptures in recent years have attracted considerable public attention and outcry due to the adverse impact on the environment of the region in the vicinity of failure. Hence there is a need for reliable methods for detecting corrosion, cracking and evaluating the structural integrity of aging pipelines. NDEL has developed and tested new technologies for ensuring accurate and consistent assessment of the safety and structural integrity of existing pipelines that include computational models for simulating Magnetic Flux Leakage (MFL) inspection of pipelines (see Figure 4) and automated signal analysis systems for rapid analysis of pipeline inspection data. This software is now deployed by industry for MFL data analysis.

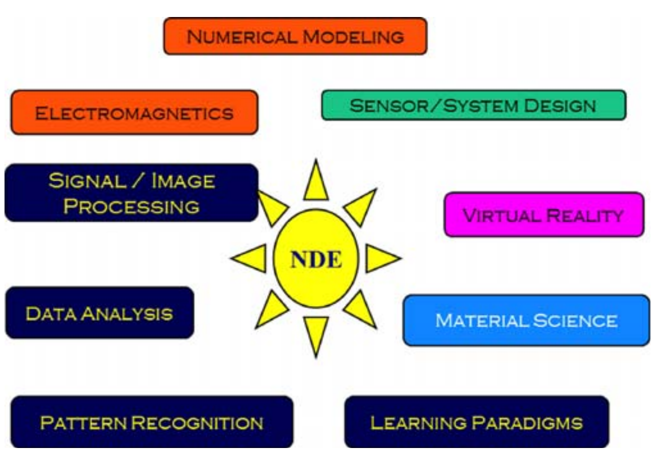

FIGURE 1. NDE: a multi-disciplinary research activity

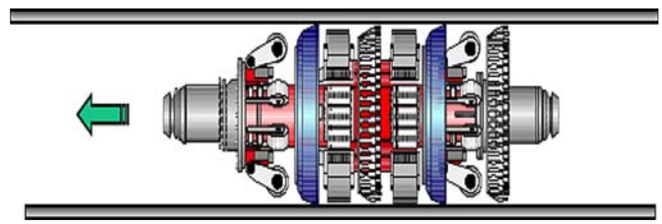

FIGURE 2. On-line MFL inspection tool

NDEL has also applied this technology to biomedical applications for detection of cracks in implanted of heart valves. Heart valves play a critical role in regulating blood flow through the cardiovascular system. Diseases of the heart valve can either be congenital or caused by infections such as rheumatic fever or endocarditis. One of the more common popular mechanical devices that was implanted extensively between 1979 and 1986 is the Bjork-Shiley Convexo-Concave (BSCC) valve. The BSCC valve consists of a pyrolytic carbon disc that serves as an occluder to block the flow of blood in one direction but allows flow in the other direction. The valve employs two struts as shown in Figure 6 to hold the disc in place. The outlet strut is TIG welded to the suture ring while the inlet strut is integral to the ring. The failure of the other weld can cause the strut to separate from the suture ring,

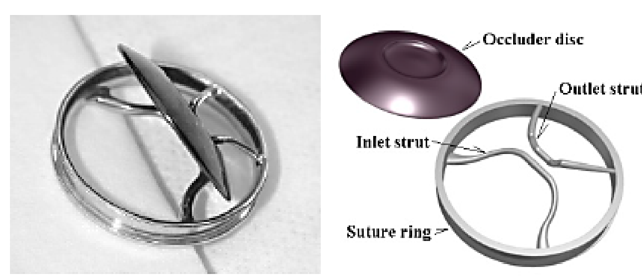

FIGURE 3. Björk-Shiley convexo-concave (BSCC) heart valve

FIGURE 4. Excitation coil assembly and the surgery table

thereby allowing the disc to detach from the valve.

Two simple electromagnetic methods for detecting strut fractures in prosthetic heart valves. The first method involves immersing the heart valve in a uniform time varying electromagnetic field and measuring the perturbation of the field in regions proximate to the strut. The second method that is currently being investigated involves the use of electromagnetic-acoustic transduction methods for exciting the resonant modes of the outlet strut. Differences between the frequencies associated with the resonant modes of intact and fractured struts are exploited to diagnose the state of the valve Figure 7 shows graduate student testing the system on a valve implanted in a sheep.

Microwave Tomography (MWT) and X-Ray Computed Tomography (CT) are conventionally utilized biomedical imaging techniques for non-invasive assessment of healthy and pathological conditions of soft and hard tissues. NDEL students are working on a conformable mirror based tomography system along with patch array antennas and fast reconstruction algorithms for application in limited angle projection data. The goals of the current research are: (1) to design and build a High Impedance Surface (HIS) mesh structure with desired reflectivity pattern, (2) to design and build a patch antenna array using HFSS simulation (Figure 8), (3) to develop accurate image reconstruction from limited projection data. Overall these novel MWT techniques will greatly improve performance and reduce current limitations.

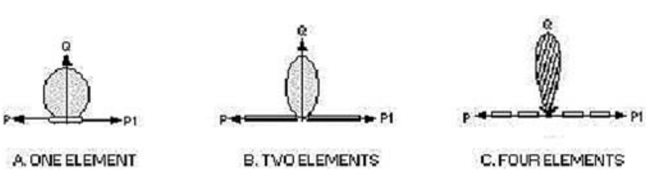

FIGURE 5. Patch antenna array design in HFSS

FIGURE 6. GE vertical x-ray inspection system with high precision rotation stage (*http://www.egr.msu.edu/erc-cleanroom/equipment/xray/index.php*)

NDEL is also working on instrumenting the GE Vertical X-Ray Inspection System with high precision rotation stage and developing fast reconstruction algorithms to provide a low cost CT tool (Figure 9).

GROUP MEMBERS

Lalita Udpa, Professor ECE; Mahmood Haq, Assistant Professor, Mechanical Engineering; Anton Khomenko, Research Associate; (12) PhD, MS, and undergraduate students

RECENT PUBLICATIONS

P. Lekeaka-Takunju, T. Khan, G. Harmon, S. S. Udpa, L. Udpa, "X-Ray Tomographic Inspection of Nuclear Fuel Rods using a Limited Number of Projections," *Materials Evaluation*, Vol. 69(4), pp. 495–500, (2011)

S. Majumdar, S. Ramakrishnan, P. Ramuhalli, L. Udpa, S. Udpa, J. Benson, R. Williams, T.U. Bipes. "Automated Data Analysis System for Steam Generator Tube Inspection," *Materials Evaluation*, Vol. 69(2), pp. 201–207, (2011)

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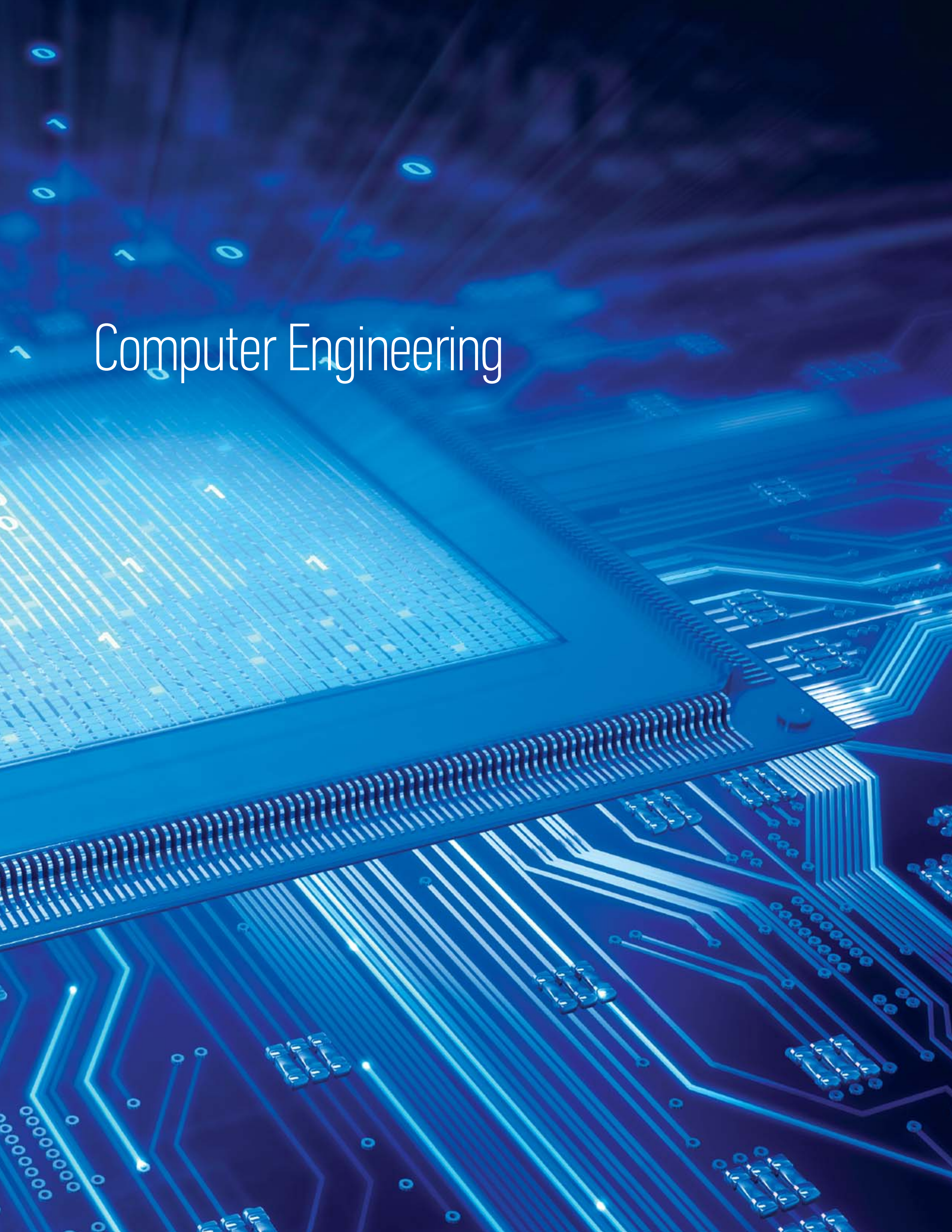
Computer Engineering



Networked Embedded and Wireless Systems Laboratory

Subir Biswas | ***sbiswas@egr.msu.edu*** | ***http://neews.egr.msu.edu***

Research in NeEWS laboratory spans across a wide range of embedded wireless networking and system design issues including resource-constrained, self-reconfigurable and cooperative network protocols, network middleware, radio spectrum scavenging, new modes of information switching in communication networks, wearable sensing for health applications, and data storage and dissemination in social wireless networks. A few representative research projects in the NeEWS laboratory are summarized below.

Networked Wearable Systems for Personalized Health Management (NIH, NASA, USDA): The objective is to develop sensing, networking, and data processing mechanisms for Connected and Personalized Healthcare infrastructure. The concepts are to sense multi-modal physiological data using low-power wearable sensors and to develop pattern identification abstractions for monitoring health dynamics for individuals. Fig. 1 depicts a metabolic energy monitoring system developed by the NeEWS lab researchers. The system constitutes: (1) a wearable sensor for swallow detection for identifying food/drink intake, (2) a set of wearable accelerometers for identifying human activity detection, (3) a 900MHz wireless network for on-body data fusion, (4) a Bluetooth network for data collection by smartphones, (5) machine learning algorithms for metabolic energy expenditure estimation and food/drink intake, and finally, (6) mobile Apps and a cloud based infrastructure for through-internet sharing and rendition to doctors, point-of-care providers, family/relatives, and the patient. Key research contributions in this project are: (1) sensor hardware system for swallow detection, (2) low-power MAC and on-body DTN routing protocols, (3) zero-exposure TDMA protocols for privacy-preserving networking, (4) machine learning algorithms for metabolic energy consumption estimation, and (5) HMM-over-Matched Filter based mechanisms for solid/liquid swallow classification via apnea detection in breathing signals. This project is a part of the MSU TRIFECTA initiative between the colleges of Engineering, Nursing, and Comm. Arts. A paper on this work won the best paper award in ICICS, April '12, Irbid, Jordan.

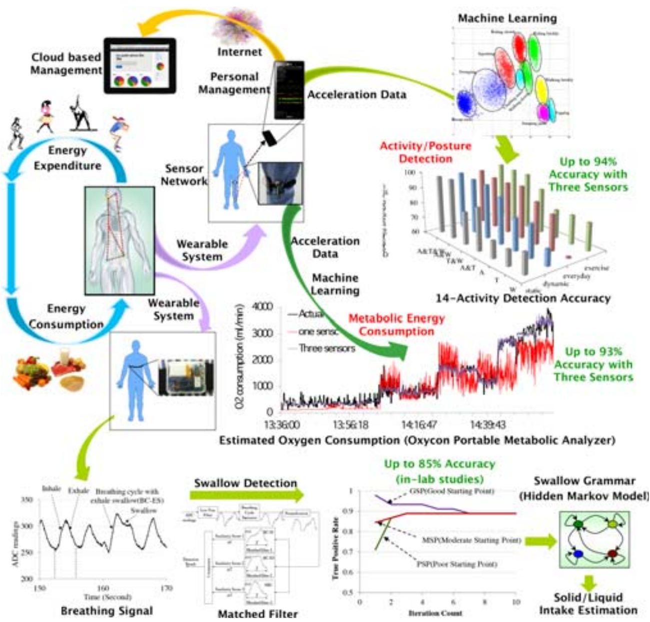


FIGURE 1. Wearable networked system for metabolic energy management.

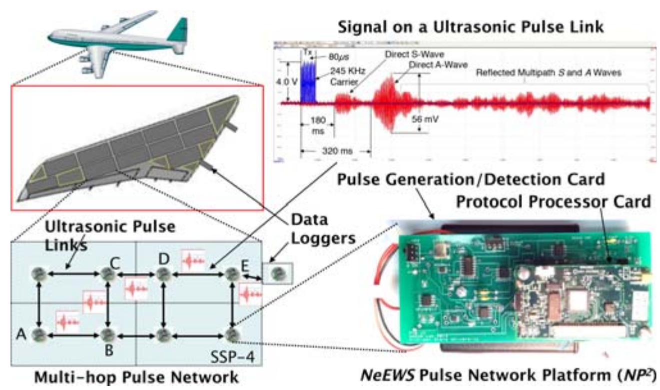


FIGURE 2. Structural monitoring using pulse networking on an aircraft wing.

Packet-less Information Networking using Multi-hop Pulse Switching (NSF): This project investigates a novel pulse switching framework for ultra-light-weight network applications. The key idea is to abstract a single pulse, as opposed to multi-bit packets, as the information switching granularity. Pulse switching is shown to be sufficient for on-off style event monitoring applications (e.g., structural health monitoring) for which a monitored parameter can be modeled using a binary variable. NeEWS lab researchers have developed a joint MAC-routing architecture for pulse switching and multi-hop routing with a novel cellular localization strategy. The feasibility and performance of this system is currently being evaluated using Ultra Wide Band (UWB) and ultrasonic pulsed data links. Fig. 2 shows a prototype system using ultrasonic pulse networking for structural health monitoring of an aircraft wing. The system uses aircraft wing substrate as the communication media for reporting fault information to data loggers through a multi-hop pulse network. Key research contributions are: (1) ultrasonic

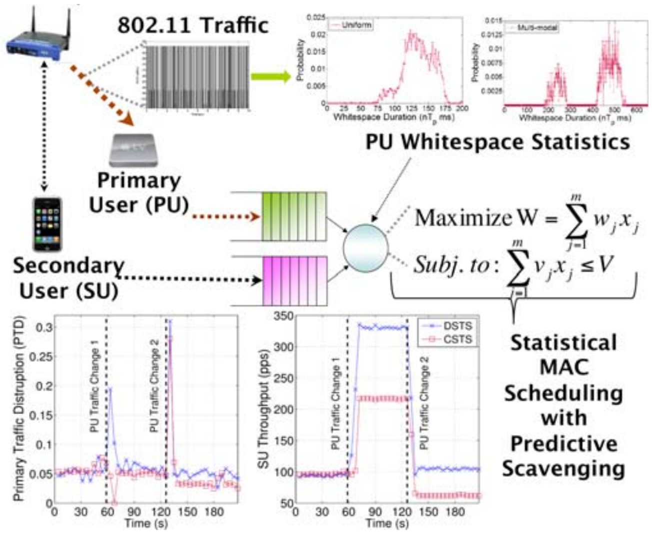


FIGURE 3. Model based predictive spectrum scavenging.

and UWB pulse modulation, transmission, and detection algorithms, (2) MAC and routing layer protocols for packet-less access and forwarding of binary information, (3) cellular event localization, (4) pulse based transport protocols for handling loss, faults, and ambient substrate noise, (5) using on-substrate event pattern recognition using spiking neural networks for implementing cognitive substrates. A paper on this work won the best paper award in ICWMC 2012, June 2012, Venice, Italy.

Bandwidth Scavenging in Wireless Networks (AFRL, NSF): Dynamic Spectrum Access can enable secondary network users to access unused spectrum, or whitespace, which is found between the transmissions of primary users in a wireless network. The design objectives for secondary user access strategy are to be able to "scavenge" spatio-temporally fragmented whitespace while limiting the interference caused to the primary users. In this project, we develop secondary user access strategies that are based on measurement and modeling of the whitespace as perceived by the secondary network users. A secondary user continually monitors its surrounding whitespace, models it as a stochastic process, and then attempts to access the available spectrum holes based on those models. Fig. 3 summarizes the bandwidth scavenging system components and their architectural relationships. Key research contributions are: (1) developing models for characterizing primary user white space and secondary user access strategies, (2) numerical evaluation of the secondary users' throughput and primary users' interference, (3) simulation for validating system effectiveness, and (4) developing a 900MHz prototype network for experimental validation and performance evaluation. A paper on this work won the best paper award in Globecom 2009, November 2009, Honolulu, Hawaii.

Resource Trading in Social Wireless Networks (NSF): Near-field communication among physically collocated mobile devices is becoming a popular means for content sharing and distribution in social wireless networks. Increasing market penetration of mobile devices and their support for short-range radio links are making such networks a distinct possibility in settings such as a University and other public places. A social wireless network captures "physical" community formation which is complementary to the "virtual" grouping in traditional social networks such as Facebook. Computing, storage, and communication resources in such networks can often be scattered and fragmented, leading to inefficient utilization. This project explores an emerging architecture that can foster economic model based resource trading in such networks for addressing the utilization issues. Network operations based on various cost and pricing models are introduced to demonstrate how by leveraging the underlying social community abstractions, fragmented storage, computing, and communication resources can be better utilized. Fig. 4 depicts a fragmented storage trading scenario developed for reducing content provisioning costs in a Social Wireless Network. The research involves: (1) stochastic formulation of cost-reward flow among the network stakeholders, (2) developing optimal distributed cooperative trading algorithms, (3) characterizing the impacts of network, user and content dynamics, (4) investigating the impacts, and developing mechanism for controlling non-cooperation, and finally (5) investigating system performance using Android based prototype Social Wireless Networks. A paper on this work won the best paper award in IEEE COMSNETS '11, January 2011, Bangalore, India.

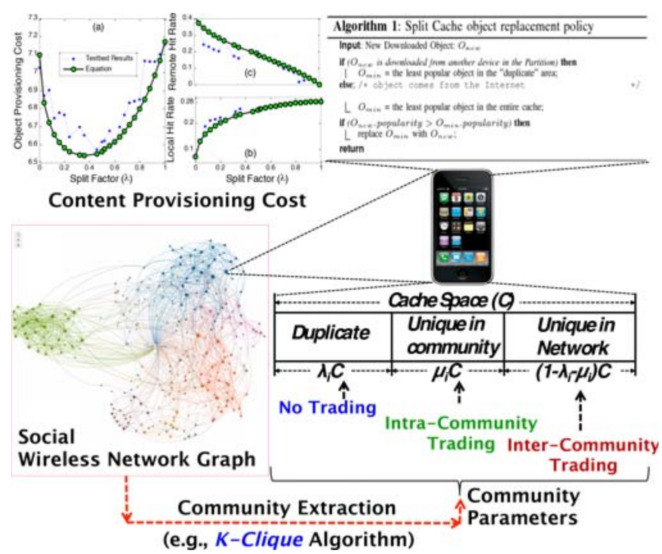


FIGURE 4. Trading of fragmented storage for content cost reduction.

CURRENT NEEWS LAB STUDENTS

Qiong Huo (Ph.D.), Debasmit Banerjee (Ph.D.), Dong Bo (Ph.D.), Stephan Lorenz (Ph.D.), Clifton Watson (Ph.D.), Faezeh Hajiaghajani (Ph.D.), Yan Shi (Ph.D.), Enkele Rama (M.S.), William Tomlinson (M.S.), and Yuan Mei (U.G.)

NEEWS LAB PUBLICATIONS

150+ papers and 26 TRs and industry whitepapers (*http://neews.egr.msu.edu/Pub.htm*)

Adaptive Integrated Microsystems Laboratory

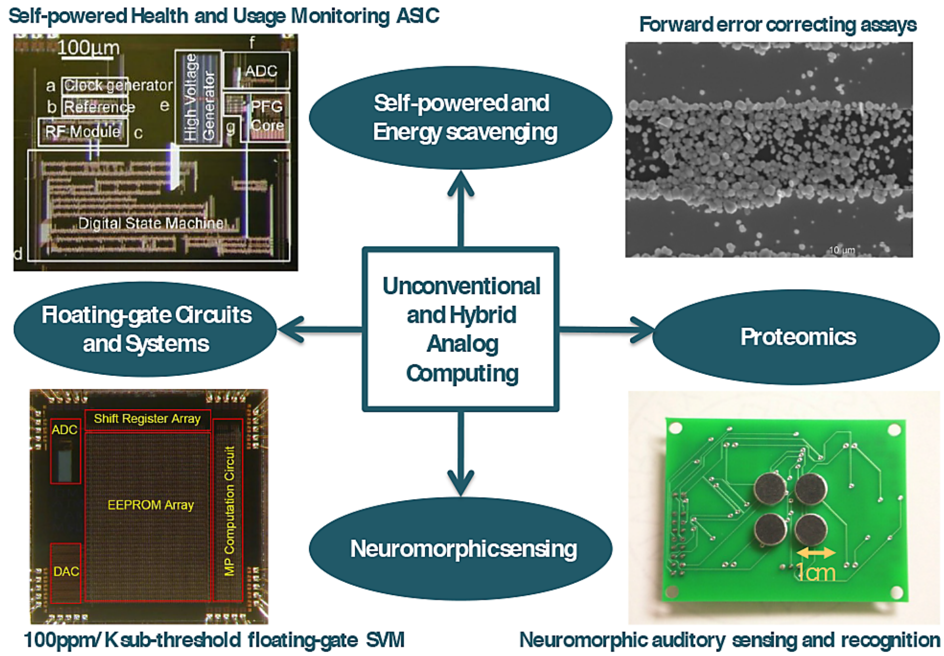
Shantanu Chakrabartty | ***shantanu@egr.msu.edu*** | ***www.egr.msu.edu/aimlab***

"Pushing the limits of analog computing and sensing"
Our research explores new frontiers in non-conventional analog computing techniques using CMOS 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.

Research in neuromorphic sensing
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. Research in our laboratory has led to the novel auditory sensing and recognition systems that exploit noise-exploitation and non-linear techniques to achieve very high energy-efficiencies and robustness. For example our variant of the silicon cochlea exploits jump-resonance type non-linearity in analog filters to achieve robustness in the presence of noise. Another variant of auditory sensor reported by our research group exploit neuronal type noise-shaping and adaptation techniques to ultra-precise source localization and source separation.

Research in self-powered sensing and battery-less circuits and systems
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 in the 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 asynchronous sensor can continuously monitor for events of interest without experiencing any down-time, a feature that can't be guaranteed with conventional synchronous 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 and hence can directly be energized by a transducer like a piezoelectric element. Based on this principle we have reported different variants of self-powered chipsets that can be used for health and usage monitoring of mechanically active parts like concrete pavements, bridges, propellers, fuselage, biomechanical implants and machine parts. We are also investigating perennial computing devices that can operate by harvesting energy from thermal noise. Because the power levels of thermal noise are typically less than 1 attowatt (10^{-18} W) , conventional electronic cannot even operate, let alone scavenge energy. We have successfully designed and demonstrated self-powered timers that operate only using ambient thermal-noise.

Research in forward error-correcting proteomics
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 process, we are investigating a forward error-correcting (FEC) approach to improve the reliability of biosensors. Our approach uses non-specific protein-based reactive 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 be only be realized using large-scale biomolecular encoders which integrates 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), which can be used for design, synthesis and verification of large-scale hybrid protein-silicon circuits.

Research in floating-gate circuits and systems

Floating-gate transistors are attractive for implementing large-scale CMOS analog VLSI processors and neural systems, because they provide an energy-efficient and a compact medium for non-volatile storage of analog parameters like currents and voltages. Using sub-threshold floating-gate techniques currents ranging over six-orders of magnitudes (fA-nA) can be programmed and stored. We have reported ultra-compact floating-gate current memories that can achieve less than 100 ppm/K of temperature stability. Also, we have reported 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.

REPRESENTATIVE PUBLICATIONS

A complete list of publications can be found at *http://www.egr.msu.edu/aimlab*.

C. Huang, S. Chakrabartty, "An Asynchronous Analog Self-powered Sensor-Data-Logger with a 13.56MHz RF Programming Interface," *IEEE Journal of Solid-State Circuits,* DOI:10.1109/JSSC.2011.2172159, vol. 47, no: 2, Feb, 2012.

M. Gu, S. Chakrabartty, "A Varactor-driven, Temperature Compensated CMOS Floating-gate Current Memory with 130ppm/K Temperature Sensitivity," *IEEE Journal of Solid-State Circuits*, vol. 47, no: 11, Nov. 2012.

Y. Liu, M. Gu, E.C. Alocilja, S. Chakrabartty, "Co-detection: Ultra-reliable Nanoparticle-Based Electrical Detection of Biomolecules in the Presence of Large Background Interference," *Biosensors and Bioelectronics,* Vol. 26, No:3, pp. 1087–1092, 2010.

K. Aono, R. Shaga, S. Chakrabartty, "Exploiting Jump-resonance Hysteresis in Silicon Cochlea for Extracting Speaker Discriminative Formant Trajectories," *IEEE Transactions of Biomedical Circuits and Systems*, (forthcoming, 2013).

Y. Liu*, S. Chakrabartty, and E. C.Alocilja, "Fundamental Building Blocks for Molecular Bio-wire based Forward-error Correcting Biosensors," *Nanotechnology*, 18, (2007), 4240172.

Computational Optimization and Innovation Laboratory

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The Computational Optimization and Innovation (COIN) Laboratory engages in research, development and application of single and multi-criterion optimization methodologies in handling various practicalities such as non-linear constraints, mixed-integer programming, large-dimensional problems, uncertainties in design variables and parameters, computationally expensive evaluation functions, bi-level problems, and dynamic optimization problems. Creation of Innovative knowledge by analyzing optimized solutions is a unique expertise and focus of COIN Lab.

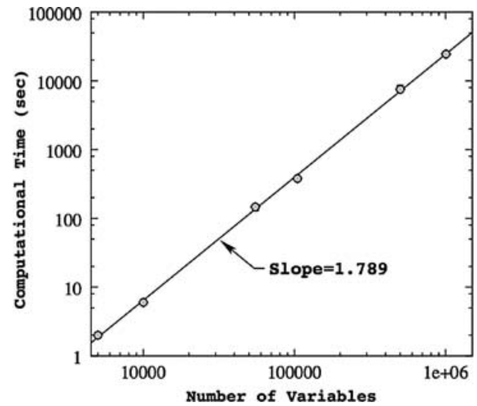

FIGURE 1. Sub-quadratic performance until 1 million variables.

Research Scope and Achievements

MODELING: Modeling objective and constraint functions for optimization from various scientific, engineering, technical, economic, and societal points of views from available data or by analyzing the problem.

DEVELOPMENT OF CUSTOMIZED OPTIMIZATION ALGORITHMS FOR LARGE-SCALE PROBLEMS: It is well established that one optimization algorithm is not efficient for solving different problems. Thus, the choice of a suitable optimization algorithm for a particular problem is as important as solving the problem itself and requires a thorough knowledge and expertise in solving different problems. Prof. Deb has been working with industries since 1995 and engaged in optimization research since 1987. Figure 1 shows results from one such application in casting sequence design for which a sub-quadratic complexity algorithm was developed (one million variable problem solved in 30 min. of computational time).

HYBRID CLASSICAL AND EVOLUTIONARY OPTIMIZATION METHODS: Evolutionary optimization (EO) methods are ideal for a global overall search in handling non-smooth, multi-modal problems. Classical methods are ideal for performing a local search in handling smooth and convex problems. One of the focuses of COIN is to hybridize classical and EO methods in a manner that makes the switch adaptively depending on the status of search and without requiring any input from the user.

NON-LINEAR CONSTRAINTS: Non-linear constraints make any search process difficult and stagnated. EO methods, due to their use of a population of points and broad search operators, are relatively less vulnerable to different complexities including non-linear nature of constraints. Prof. Deb developed parameter-less constraint handling approach ([1] with 1,595 citations) that is now used as default by EC researchers.

MIXED-INTEGER PROBLEMS: Many problems in practice involve discrete, integer, and continuous variables. Some problems also involve a schedule or a connectivity that is often represented as a permutation of a number of objects. Prof. Deb's GeneAS [2] uses binary, real-parameter, and order-based genetic algorithms (GAs) for handling such problems. Simulated Binary Crossover (SBX) ([3] with 1,140 citations) and polynomial mutation operators [8] made significant impact in solving real-parameter optimization problems using GAs.

COMPUTATIONALLY EXPENSIVE PROBLEMS: Many engineering design and process optimization problems involve expensive evaluation methods—use of FEM, CFD, flow-solvers are common. Some such problems are stochastic and require multiple evaluation schemes. COIN has developed computationally efficient meta-modeling methods based on Kriging, SVM, and response surface techniques that work with constraints and multiple objectives. COIN has also developed efficient integration schemes of combining meta-modeling with EO algorithms for a faster overall application.

OPTIMIZATION WITH A BUDGET: Many practical problems prespecify a limit on the use of overall number of solution evaluations based on the availability of expected time. COIN has developed computationally efficient algorithms for allocating solution evaluations optimally among meta-modeling method, available parallel computing hardware, and hybrid classical-EO methods for single and multi-objective problems.

MULTIPLE OPTIMAL SOLUTIONS: Many practical problems has multiple global and many local optimal solutions worth a consideration. Practitioners are often interested in finding not one, but a few global and local optimal solutions. Prof. Deb is a pioneer in multi-modal EOs for finding multiple optimal solutions in a single simulation and developed efficient "niched GAs" [4], [5]. Knowledge of multiple optimal solutions provide an opportunity to practitioners to first have a look at different alternate optimal solutions before choosing a single preferred solution.

MULTIPLE CONFLICTING OBJECTIVES: No optimization problem in practice involves a single objective function. Cost and quality are two usual conflicting objectives of a design. Such multi-objective optimization problems give rise to multiple Pareto-optimal solutions. Prof. Deb has championed in developing efficient evolutionary multi-objective optimization (EMO) methods since 1994 and remains world's leading expert in the field. His NSGA ([6] with 3,897 citations) and NSGA-II ([7] with 9,868 citations) are most popular methods in all areas of EC. COIN Lab continues to develop innovative methods in EMO and extend them to address various practicalities encountered in practical problems.

MULTI-CRITERION OPTIMIZATION AND DECISION-MAKING: In multi-objective optimization task, there is a need to choose a single preferred solution for its implementation. Prof. Deb has worked with Multiple Criteria Decision Making (MCDM) researchers to integrate efficient MCDM methods with EMO so that a decision making aid can be used *a priori*, *a posteriori*, or in an interactive manner [8],[9]. COIN Lab leads in this area of providing a complete solution to multi-objective optimization task, rather than finding just a set of trade-off solutions.

OPTIMIZATION WITH UNCERTAINTY: When design variables or associated problem parameters (including environmental conditions) are uncertain, what good is an optimal solution that is often isolated and overly sensitive to uncertainties? COIN Lab has developed "robust" single and multi-objective optimization methods that are capable of finding robust (instead of optimal) solutions that are relatively insensitive to uncertainties [10]. Optimal solutions are also risky for violating constraints in presence of uncertainties. COIN Lab's research in developing *reliability* based, *evidence* based, and *Bayesian* based optimization methods are significant steps in making evolutionary optimization closer to practice.

MANY CONFLICTING OBJECTIVES: There exist many problems (involving societal and large-scale "wicked" problems) that involve five or more objectives. These so-called many-objective optimization problems require special dimension-handling optimization methods. COIN Lab's latest research (development of NSGA-III) and its applications are significant contributions to optimization. NSGA-III is shown to solve up to 15-objective problems efficiently.

"INNOVIZATION"—INNOVATIVE KNOWLEDGE CREATION: Multiple high-performing trade-off solutions found from an EMO can be utilized to reveal vital properties common to the solutions. They provide "signature" properties of optimal solutions. Naturally, once found, they would provide new and innovative solution principles that dictate "how to create an optimal solution?" [11]. COIN Lab has recently developed machine learning procedures for finding "innovized" principles as rules and decision trees hidden in trade-off multi-objective data. COIN Lab's research in this direction rejuvenates the importance of using optimization task in practice and provides a new meaning to the use of optimization in practice.

MULTIOBJECTIVIZATION: The principle of using at least two conflicting objectives and finding multiple trade-off solutions before choosing a single preferred solution can be extended to solve different problem-solving tasks including data mining and many single-objective optimization problems. COIN has developed efficient multi-modal optimization and constraint handling methods and continues to apply the concept to other problem areas.

PARALLEL AND DISTRIBUTED OPTIMIZATION METHODS: EO methods are highly parallelizable. COIN Lab uses latest GPU based hardware and parallel computers to develop computationally faster algorithms (making 500–1,000 times faster than a single-processor application) for both single and multi-objective optimization problems.

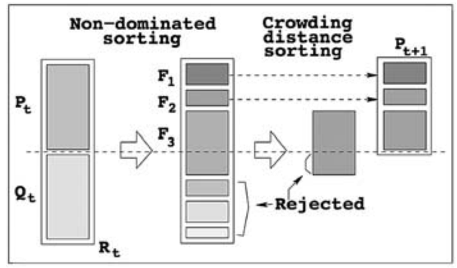

FIGURE 2. NSGA-II procedure is illustrated.

BI-LEVEL OPTIMIZATION PROBLEMS: Many practical problems involve two nested optimization tasks—an upper level optimization makes a solution feasible if it corresponds to an optimal solution of a lower-level optimization problem. Control problems, transportation problems, and structural design problems are some examples. Prof. Deb has pioneered in developing efficient methods for single and multi-objective bi-level problems.

DYNAMIC OPTIMIZATION PROBLEMS: Most problems in practice are dynamic in nature—the problem changes as the optimization task is ongoing. Prof. Deb has proposed efficient algorithms for handling dynamic problems in two different ways—off-line rule generation and "frozen-time" methods.

PRACTICAL OPTIMIZATION: A major hallmark feature of COIN Lab is to solve practical problems. Prof. Deb helped develop "evORElution" software (for an Australian company "Orelogy") for finding optimized mine schedules having multi-million variables. A recent collaborative work with NSF Beacon Center's Director Prof. Erik Goodman and New Zealand's Forest Research Lab scientist Dr. Oliver Chikumbo has resulted into an award-winning many-criterion application. Prof. Deb and COIN Lab plan to continue to work with industries and academics in solving challenging problems.

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Engineering Applications of Evolution in Action and Genetic Algorithms Research and Applications Group

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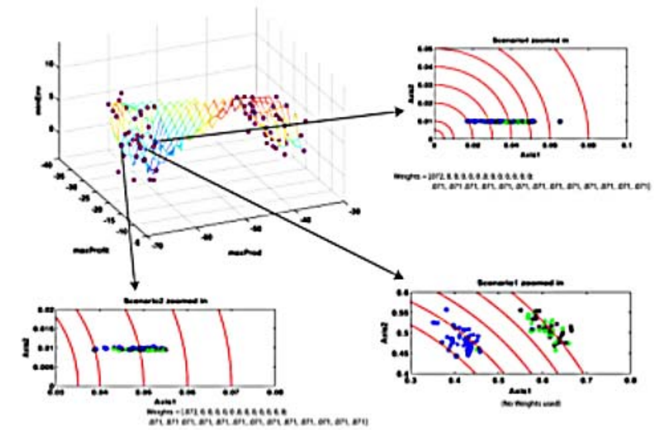
BEACON, an NSF Science and Technology Center directed by Goodman, has three themes dealing with evolution in action—biological evolution, digital evolution and evolutionary applications—and Goodman's research deals with the third theme, namely, applications of evolutionary computation to solution of a variety of engineering design and related problems. While classical evolutionary algorithms (genetic algorithms, genetic programming, etc.) have been widely used for many years, many challenging problems cannot be practically addressed using "out of the box" methods. Goodman, his colleagues, and their students develop new forms of evolutionary computation, largely driven by lessons learned from research in BEACON's other two themes and other discoveries about evolution in action. Goodman currently participates in five active projects (among BEACON's 50 or so), as described briefly below.

Multi-Criterion Decision Making in Rural Land Use Management by Evolutionary Multi-Objective Optimization

TEAM: *Oliver Chikumbo (Scion, New Zealand), Kalyanmoy Deb (MSU), Daniel Couvertier (CSE, Ph.D.), EDG*

This project is aimed at demonstrating that one of society's "wicked" problems, land use management, can be successfully addressed through the use of multi-criterion decision making supported by evolutionary multi-objective optimization. The method begins with a set of models for (in this case, 14) objectives of importance to various stakeholders. An advanced EMOO method, R-NSGA-II, is enhanced by addition of epigenetic operators, based conceptually on recent advances in understanding of epigenetics in nature. This method makes it practical to find a useful 4-dimensional Pareto Surface, or to visualize a 3-dimensional Pareto surface generated by merging related objectives to reduce problem dimensionality. Stakeholders are presented various tradeoff possibilities and asked to rank their preferences, thus introducing the "social" component of the triple bottom line, which includes social, economic, and environmental effects. Then only the best choices for a small number of land use plans need to be introduced to the stakeholders for their consideration. Experience to date shows that good compromises can be readily identified with such a process.



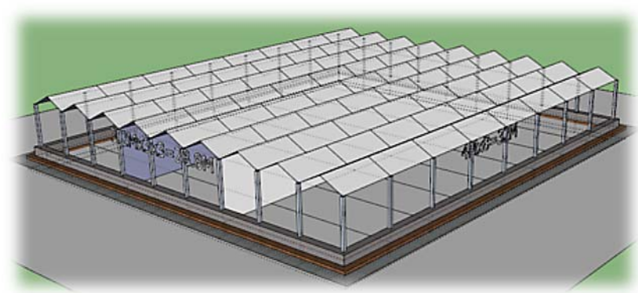


FIGURE 1. A new greenhouse is nearing completion at Tongji University (Shanghai, CHINA), where the control methodology will be parameterized and tested.

Robust Multi-objective Evolutionary Optimization for Greenhouse Production/Energy Tradeoffs

TEAM: *Prof. Lihong Xu (Tongji U.), Chenwen Zhu (visiting Ph.D. student from Tongji U.), Prakarn Unachak (Pdoc, BEACON), Jose Llera (Ph.D., ECE), Dave Knoester (NSF Postdoc, BEACON), EDG*

The project is heavily funded in China to develop a new generation of energy-efficient greenhouses. The team at MSU is working on developing an advanced controller

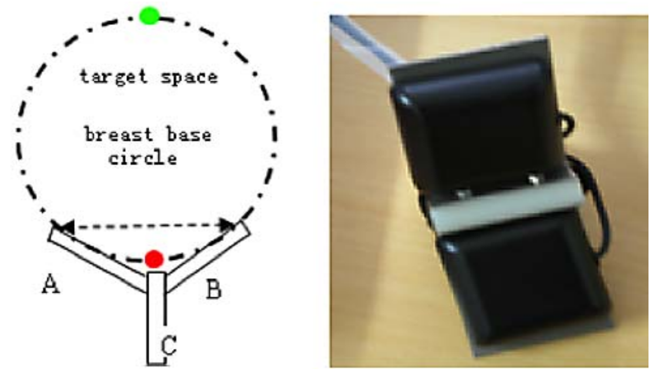


FIGURE 2. (*left*) Depiction and antenna structure of BRATUMASS: transceiver (red dot) and metal slice (green dot) are positioned at 16 different angles around the circumference of the breast; (*right*) ultrawideband microwave transceiver antenna.

using the Multi-Objective Compatible Controller method developed by the team, relying on sophisticated evolutionary multi-objective optimization to identify the Pareto front and a flexible operating regime for the greenhouse on or near that front. Sophisticated modeling of both the microclimate and the crop production are needed to enable this control algorithm.

Evolutionary Algorithms for Enhanced Ultra-Wideband Microwave Imaging of Breast Cancer

TEAM: *Prof. Meng Yao* (*East China Normal University*), *Prof. Jack Deller* (*ECE*), *Dave Knoester* (*NSF BEACON Postdoc*), *Blair Fleet* (*ECE, Ph.D.*), *Jinyao Yan* (*ECE, Ph.D.*), *EDG*

Prof. Meng's team in China has developed antenna hardware to allow harmless microwave signals to penetrate breast tissue and produce returns that contain identifiable returns from area of sharp change of dielectric constant, such as tumor boundaries. Explorations here center on finding effective ways of correlating these signals from 16 directional observations and evolving features to classify the ensemble as indicating or not indicating presence of a tumor. Success could lead to development of screening methods much less harmful than the current x-ray-based mammography.

Modeling Metabolic Gene Clustering in Bacterial Chromosomes using a Custom-crafted Computational Evolution Platform

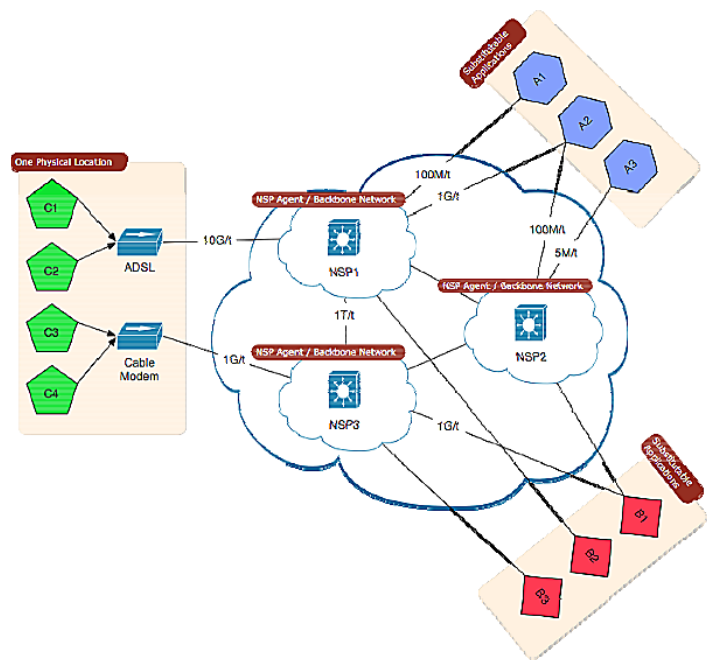
TEAM: *Prof. Julius Jackson* (*MMG, MSU*), *Gowon Patterson* (*CSE, Ph.D.*), *EDG*

Patterson is developing a computational evolution software platform to enable him to conduct research investigating the hypothesis that in bacteria, high local concentrations of enzymes associated with a particular metabolic pathway near the site of transcription/translation produce sufficient selective pressure (via speedup of protein synthesis on that pathway) to generate tight linkage of the enzymes in the pathway.

Evolving a Telecommunications Ecosystem

TEAM: *Prof. Johannes Bauer* (*TISM, MSU*), *Prof. Kurt DeMaagd* (*TISM, MSU*), *Matthew Rupp* (*Pdoc, MSU*), *Kendall Koning* (*CSE, Ph.D.*), *EDG*

We seek to understand the development of the infrastructure and services provided by the Internet by examining the emergent properties of an evolving, complex model of the telecommunications marketplace. We use a bottom-up approach to model the telecommunication marketplace with both fully-specified agents and agents evolving using the Simternet software we are developing.



ACKNOWLEDGMENTS

Financial support for Goodman's teams is provided by the National Science Foundation (through BEACON—DBI-0939454 and through grant CDI-0941310), by the National Natural Science Foundation of China and other agencies supporting work of his Chinese collaborators, and through Scion, a Crown Research Corporation in New Zealand.

Advanced Circuits, Architecture, and Computing Laboratory

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Advanced Circuits and Architectures

In the past, semiconductor technology scaling and circuit and architecture innovations have delivered exponential performance growth within roughly fixed power and cost budgets. This has yielded wide ranging benefits across all sectors of the economy by making software increasingly powerful (to solve compute-intensive problems), easier to develop (through high-level languages and tools that enhance software productivity), and more cost effective (e.g., by enabling distributed cloud computing applications supported by advertisement revenue). However, extremely scaled technologies pose a number of challenges to this trend: the fraction of the transistor budget on a chip that can be actively engaged at any given time within fixed power and thermal constraints is decreasing in current architectures, devices are becoming more unreliable (because of process, voltage, and temperature variations and susceptibility to soft and hard errors), and communication and memory access are becoming increasing bottlenecks. Further, emerging applications demand greater security and are data intensive.

To address the above challenges, we have developed a number of advanced circuit- and architecture-level techniques for modeling and design optimization that exploit the fact that the behavior of computation, communication, and storage components on a chip are dependent on the data value and timing of signals they process. Examples of these include spatio-temporal energy and thermal modeling of on-chip interconnects, operand encoding and operation bypass techniques for computation components, static, dynamic, and adaptive encoding techniques for interconnects, and interconnect and memory system compression. Our current research is focused on cross-layer design techniques suitable for extremely scaled technologies, for modern computing infrastructure (sensors, portable edge devices, and cloud servers), and for meeting the demands of emerging big data and security-sensitive applications.

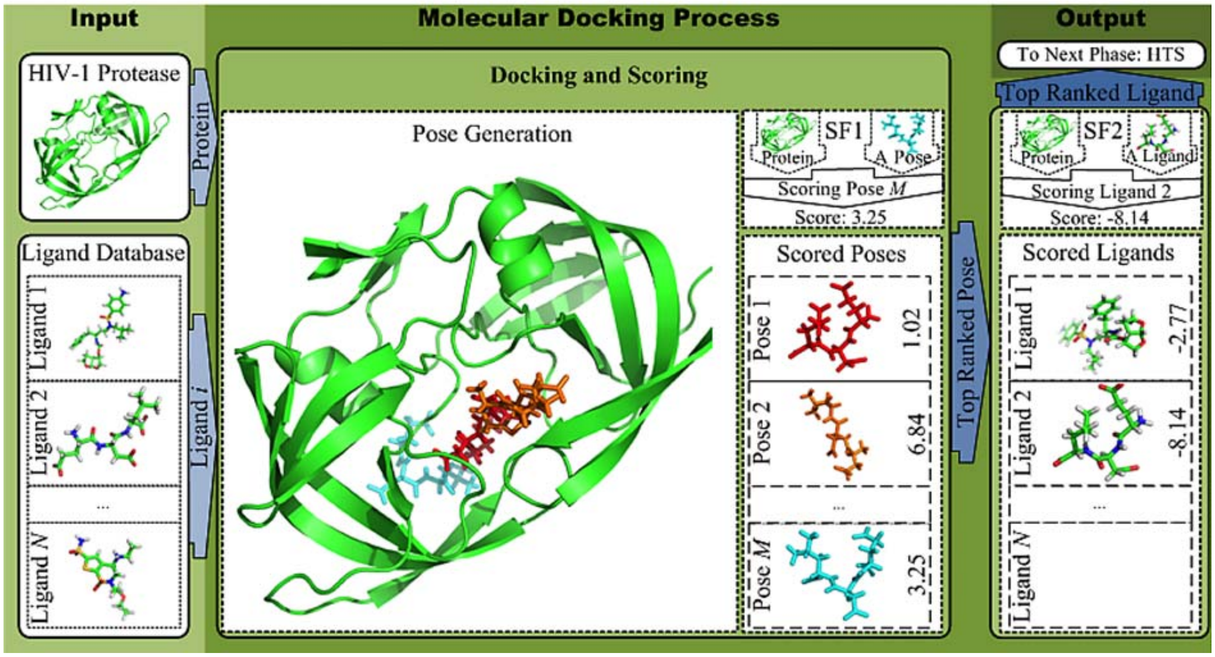
Advanced Computing

We have designed efficient sequential and scalable parallel branch-and-bound algorithms for solving hard discrete optimization problems. Our current efforts are centered on machine learning and optimization algorithms for big data and bioinformatics problems. We are also applying computational principles to natural and engineered systems (e.g., cyber-physical systems) to solve problems, develop design methods, facilitate automation, and advance understanding of their behavior.

Structure-Based Drug Design

Drug design involves two main steps: first, the enzyme, receptor, or other protein responsible for a disease of interest is identified; second, a small molecule or *ligand* is found or designed that will bind to the target protein, modulate its behavior, and provide therapeutic benefit to the patient. The process of finding ligands that bind strongly to a macromolecular target involves screening millions of them. Determining the binding affinity (BA) of each ligand against a target protein *in vitro* and/or *in vivo* is a prohibitively expensive process and impractical for large databases even with the use of high-throughput screening approaches. As a result, *in silico* virtual-screening techniques are employed to filter large compound databases to manageable sets of most promising ligands. Molecular docking (*see figure*) is a popular computational approach that "docks" a ligand into the 3D structure of macromolecular target and scores its potential complementarity to the binding site by predicting its BA.

Accurately predicting the BAs of large sets of protein-ligand complexes efficiently is a key challenge in computational biomolecular science, with applications in drug discovery, chemical biology, and structural biology. Since a scoring function (SF) is used to score, rank, and identify potential drug leads, the fidelity with which it predicts the affinity of a ligand candidate for a protein's binding site has a significant bearing on the accuracy of virtual screening. Despite intense efforts in developing conventional SFs, their limited accuracy



has been a major roadblock toward cost-effective drug discovery. To address this problem, our research focuses on the development of highly accurate machine learning SFs in conjunction with a variety of physicochemical and geometrical features characterizing protein-ligand complexes for the ligand docking, scoring, and ranking problems. Our efforts to date have yielded a machine learning SF with a predictive accuracy of 0.809 in terms of Pearson correlation coefficient between predicted and measured BA compared to 0.644 achieved by a state-of-the-art conventional SF on the core test set of PDBbind benchmark.

ACKNOWLEDGMENT

Research is supported in part by the U.S. National Science Foundation.

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CURRENT GROUP MEMBERS

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Advanced MicroSystems and Circuits Laboratory

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The mission of the AMSaC research group is to develop integrated circuit and microfabrication approaches that enable a bridging between novel nano/micro-sensor technologies and high impact biomedical and environmental monitoring applications. Our recent activities are highlighted below.

Recent News

- JANUARY 2013: Cover article for *IEEE Trans. Neural Sys Rehabilitation Engineering*
- NOVEMBER 2012: AMSaC lab presents a paper at IEEE BioCAS Conference in Hsinchu, Taiwan
- MAY 2012: AMSaC lab presents two papers at the IEEE ISCAS Conference in Korea
- SPRING 2012: Xiaoyi Mu's IEEE ISCAS paper receives the Sensory Systems TC Honorary Mention Paper Award
- FALL 2011: Dr. Mason serves as a General Chair of 2011 IEEE BioCAS Conference
- NOVEMBER 2011: AMSaC lab presents four papers at IEEE BioCAS Conference in San Diego
- AUGUST 2011: AMSaC lab presents two papers at IEEE Eng. Medicine Biology Conference in Boston
- JUNE 2011: Dr. Mason delivers keynote talk at IEEE Inter. Workshop Advances Sensors Interfaces, Italy.
- FALL 2010: AMSaC paper receives the IEEE BioCAS 2010 Best Student Paper Award
- FALL 2010: Dr. Mason receives $1.9M R01 grant to develop gas sensor arrays for underground mine safety
- SPRING 2010: Dr. Mason receives the 2010 Withrow Award for Teaching Excellence

Electrochemical Gas Analysis Microsystem

Xiaoyi Mu (PhD student) and *Haitao Li* (PhD student)

Despite continued safety improvements and increased regulations, underground mines remain a very dangerous work environment. To prevent explosions and exposure to toxic gas concentrations, new gas sensors that are low-cost, low-power, reliable, portable, and capable of real-time monitoring are needed. Although numerous gas sensors have been developed, real-time explosive and toxic gas monitoring devices that can be widely distributed in mines still do not exist.

We are developing several key sensor technologies to form a miniaturized *intelligent electrochemical gas analysis system* (iEGAS) tailored to the needs and challenges of mine safety applications. The electrochemical sensor array under development is capable of measuring concentrations of several gases to predict and prevent fires and explosions (CH_4, O_2, etc.) and to limit worker exposure to hazardous exhaust gases (SO_2, etc.). Customized sensor instrumentation IC chips are being developed to record sensor responses to multiple electrochemical measurement techniques.

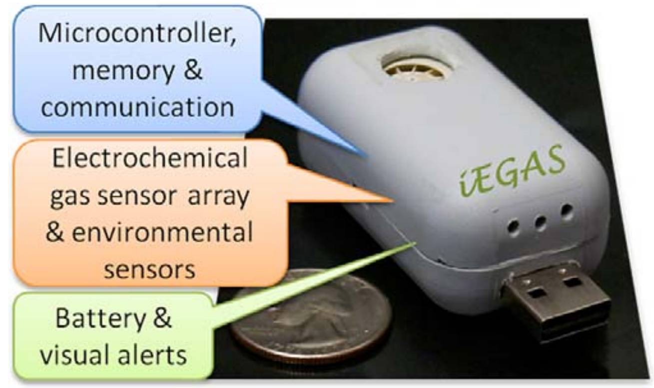

FIGURE 1. Components of the iEGAS wearable gas analysis microsystem in a USB thumb-drive package.

The integrated *iEGAS* prototype is small enough to carry or wear without encumbering mine personnel, and it is capable of autonomous communication with a PC or wireless device for uploading recorded data. Further research is underway to realize an autonomous system that will integrate electrochemical sensor arrays, electrochemical instrumentation circuits, and low-power sensor array classification algorithms running on an embedded microcontroller to provide maintenance-free operation and intelligent self-management and self-correcting features.

Multi-function Electrochemical Biosensor Microsystem

Xiaowen Liu (PhD student) and *Lin Li* (PhD student)

Advances in microelectronics and lab-on-chip devices have enabled the development of highly integrated biosensor arrays on the surface of CMOS instrumentation chips to provide a low cost, high resolution, and high throughput solution for quantitative measurement of a wide range of biochemical analytes. The resulting miniaturized biosensor microsystem can be applied to point-of-care diagnostics, environmental monitoring, drug screening, and other healthcare applications.

The goal of this project is to develop an integrated microsystem platform that incorporates an array of biological recognition interfaces, CMOS electrochemical characterization circuits, and microfluidics for continuous-use, cost-effective, biochemical analysis. We have explored several

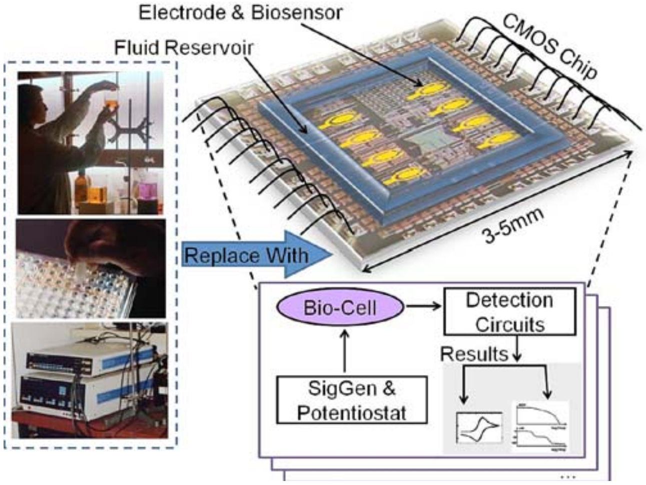

FIGURE 2. Multi-function electrochemical biosensor microsystem to replace bulky benchtop sample analysis tools with a highly integrated CMOS-based array device.

interdisciplinary technical challenges including: (1) the development of novel nanostructured bio-interfaces appropriate for integration with a microelectronics chip, (2) the design of high performance integrated circuits for multiple electrochemical assays, and (3) the development of microfabrication and packaging techniques enabling a miniaturized, lab-on-CMOS platform with microfluidics. Electrode arrays on silicon have been fabricated and functionalized with nanostructured enzyme and membrane protein interfaces. A new bioelectrochemical readout circuit has been developed that realizes both impedance spectroscopy and amperometry techniques while sharing hardware resources to minimize power and area. Several packaging options are now being explored to integrate all of the microsystem elements, enabling rapid characterization of proteins and development of new biosensor platforms.

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AMSAC TEAM

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Cyber Security Laboratory

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The mission of the Cyber Security Lab at Michigan State University is to design and develop crypto-graphic algorithms and network security protocols for the next generation Internet, wireless net-works, ad-hoc and sensor networks where power efficiency and security are of major concerns. The expertise of the Cyber Security Lab also includes secure digital copyright protection and management. Cyber Security Lab has both hardware and software platforms for design and evaluation of the secure communication systems. Our research has been supported by National Science Foundation, Air Force Research Labs, and an industry partner. Below is a list of some projects in the Cyber Security Lab.

Cost-Aware Privacy-Preserve Communications

Privacy-preserving communication is a key requirement for many security applications. The existing research on privacy-preserving communications lacks fundamental security measurement criteria and unable to provide provable security service. In this project, for the first time, we developed quantitative security measurement criteria. Based on these criteria, we identified security weaknesses of some existing schemes.

For the first time, we introduced cost-aware security scheme design and we have developed cost-aware and provably secure routing schemes. Our model provides an elegant cost-aware security design trade-off. This model can be applied in a variety of network scenarios. A routing based cost-aware privacy-preserving scheme is illustrated in Figure 1 with security level 0 and 0.5.

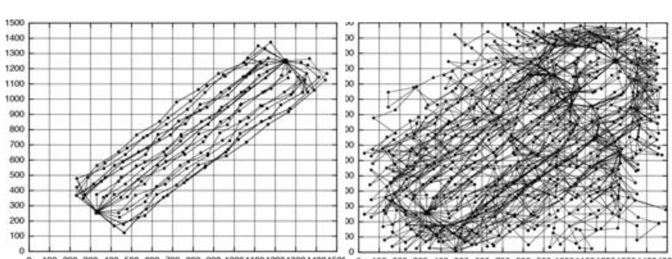

FIGURE 1. Routing path distribution for security parameter 0 and 0.5.

Design of Pollution-resistant Network Coding Schemes

Network coding (NC) is a newly proposed communication paradigm that can save the bandwidth for multicast flows in direct networks. However, the benefit of the NC is only achievable in networks consisting of only reliable and trustworthy nodes since even very small network pollution can defeat the entire communications.

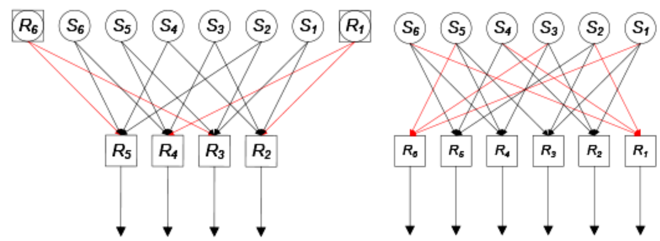

FIGURE 2. Illustration of code-adaptive NC.

In this research, we first proved that each NC could be mapped into an error-control coding (EC). Based on this result, we developed a rate adaptive NC architecture through adaptive relay selection in the bipartite to identity and remove the network pollution as illustrated in Figure 2, where the code is adapted from (12, 8) (Figure 2A) to (12, 6) (Figure 2B). We also investigated combating NC pollution using LDPC decoder.

Our analysis shows that our proposed NC scheme can achieve a high throughput even for a heavily polluted network environment.

Secure Access and Management Platform Design and Development for Smart Home and Smart Grid

Smart grid/home is a key interface for electric power and home automation. In fact, smart home is transforming the home to an intelligent organism, a living, breathing life form. A physical architecture for the smart grid and smart home is given in Figure 3. A key component for smart grid/home is the Secure Access Gateway (SAG), which enables the home electronic device to be remotely controlled and operated.

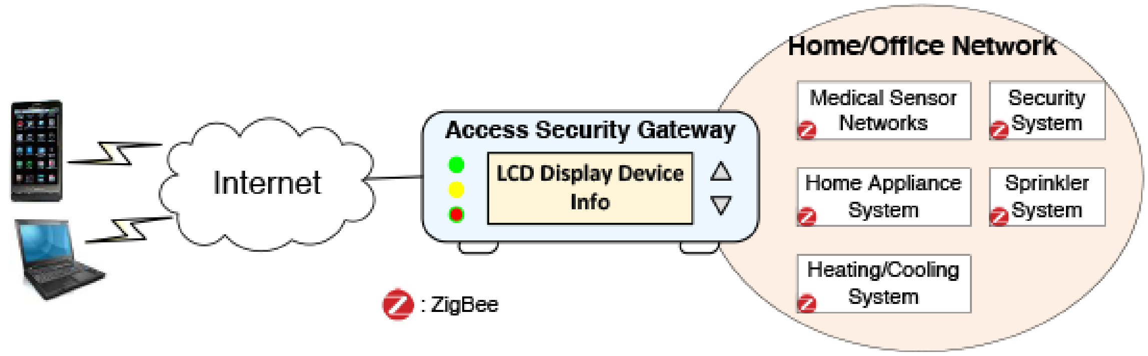

FIGURE 3. Smart grid/smart home architecture.

In this project, we have developed an SAG platform (Figure 3). The SAG platform has an Ethernet interface and also a ZigBee interface. With the Ethernet interface, we can remotely access SAG from either an Android smartphone or a PC. While the ZigBee interface enables the SAG to securely communicate with and manage ZigBee ready home electronic devices. For the SAG, we put special emphasize on the security protection and management. We have developed both one-time login name and one-time cryptographic authentication schemes for SAG based on our own cryptographic algorithms. The unique design makes SAG secure from security attacks.

We also developed software for Android smartphones (Figure 5). The software enables us to securely remote connect to the SAG and the devices protected by the SAG through the ZigBee interface.

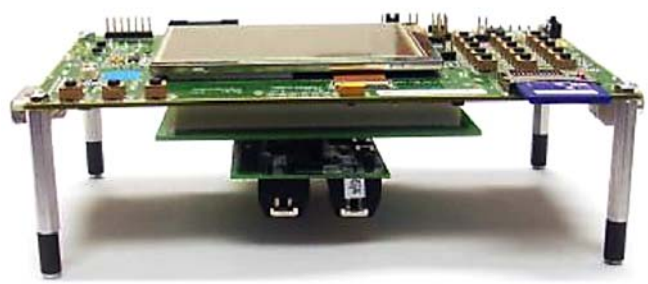

FIGURE 4. Secure Access Gateway (SAG) developed at Cyber Security Lab and BAWC Lab.

FIGURE 5. Android smartphone remote and management interface.

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ACKNOWLEDGEMENT

The research of Cyber Security Lab is supported by multiple National Science Foundation awards.

Circuits, Systems, and Neural Networks Laboratory

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The CSANN lab presently focuses on two activities: (1) the design of integrated electronic circuits (ICs) and systems, including the radio-frequency (RF) range, with a view towards integrating sensing, (magnetic) actuation, and processing in (CMOS) VLSI industrial fabrications; (2) spiking neuronal networks modeling from brain science, their synchrony, asynchrony and interactions coupled with developing and validating self-learning optimal estimation, detection, and extraction of signals and information from streams of measurements or data.

Integrated sensing and actuation systems for cell and protein sensing and control *(see Figures 1 & 2)*

(Superparamagnetic) beads are increasingly used in biomedical assays to manipulate, transport, and maneuver biomaterials (cells, proteins, etc.).

This effort focuses on low-cost integrated system designed in bulk CMOS—in order to leverage computational powers, precision and speed. The integrated system is to manipulate and separate biomaterial tagged with magnetic beads.

The integrated systems include insulated open cavity coil-arrays suitable for sensing and generating directed magnetic (fields and) forces for single biomaterial, or collaborative multi-bead manipulation, using pseudo-parallel executions.

Several initial lab experiments have been conducted to validate and metrically quantify this approach. The results have demonstrated the effect of the generated magnetic forces on magnetized micro-beads. The total power consumption of the entire module on average is 9mW when running at full power. For further details, see publications [1, 2] at the end.

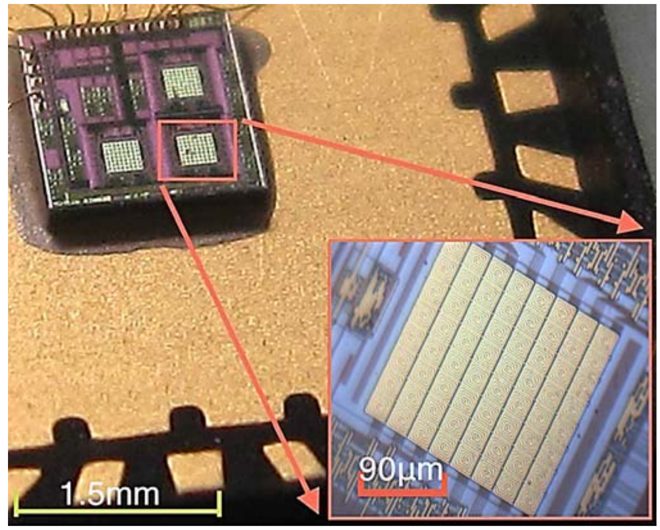

FIGURE 1. Photograph of 1.5mm × 1.5mm CMOS die as an open

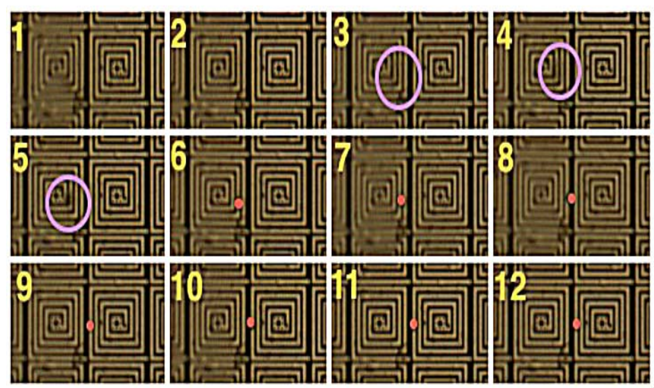

FIGURE 2. A montage of a series of video frames showing how a magnetic bead is pulled towards a coil then is moved to the right by switching on the neighboring coil.

Adaptive Self-learning Systems

Motivated from aspects of the brain and mathematical formalism, we are developing autonomous (or unsupervised) stochastic adaptation approaches that recover original signals from mixers in realistic environments that may include convolution, transients, and even possible nonlinearity. The primary goal here is to recover original source signals, as best as possible, even in the absence of precise environment knowledge.

An optimization framework that includes state-space modeling, using the Riemannian contra-variant gradient adaptation has been developed.

The framework has been successfully applied for (cellphone) Blind Multi User Detection (BMUD) in modern (Code Division Multiple Access) CDMA wireless communication networks. Promising results clearly

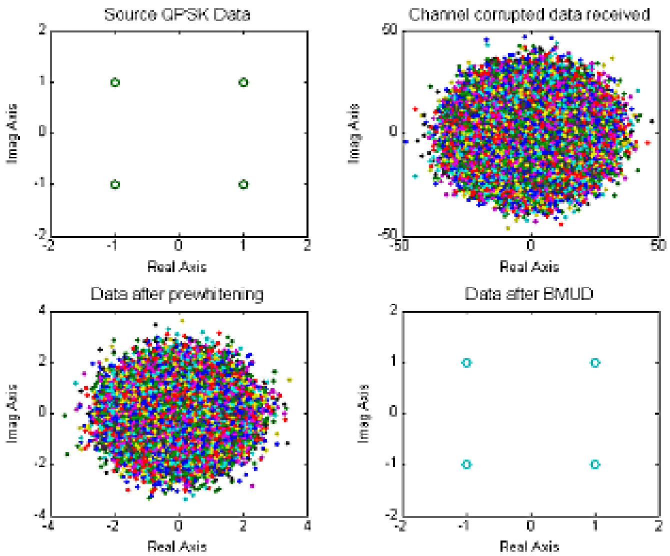

FIGURE 3. Depicts (i) symbol code, (ii) received mixtures, (iii) pre-whiting, then (iv) source symbol recovery.

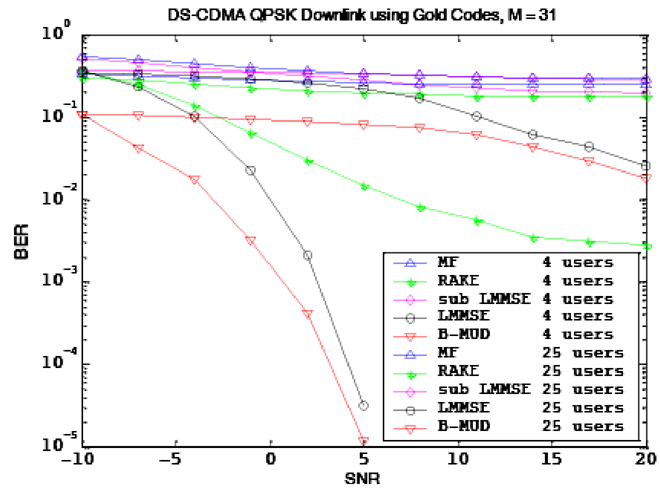

FIGURE 4. Superior Detection Performance compared to leading methods with phase of primary path unknown.

demonstrate the effectiveness and practicality of the formulated approach.

Blind Multi User Detection (BMUD) is the process of simultaneously estimating multiple symbol sequences associated with multiple users in the downlink of a (CDMA) communication system using only the received data. Figures 3 and 4 show an example performance of the adaptive algorithms is recovering the symbol sequences constellation after channel propagation and attenuation. Fig. 4 shows the superior BMUD performance in terms of the standard Bit-ERROR-Rate (BER).

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ACKNOWLEDGEMENT

Support in part from the National Science Foundation (EECS) , SBIR/STTR in collaborations with IC Tech Inc. Also thanks to all current students, Lab team and collaborators.

Control, Robotics, and Power

NanoRobotic Systems Laboratory

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Progress in robotics over the past years has dramatically extended our ability to explore the world from perception, cognition and manipulation perspectives at a variety of scales extending from the edges of the solar system down to individual atoms. At the bottom of this scale, technology has been moving toward greater control of the structure of matter, suggesting the feasibility of achieving thorough control of the molecular structure of matter atom by atom. Nanorobotics represents the next stage in miniaturization for maneuvering nanoscale objects. Nanorobotics is the study of robotics at the nanometer scale, and includes robots that are nanoscale in size and large robots capable of manipulating objects that have dimensions in the nanoscale range with nanometer resolution. The main goals of nanorobotics are to provide effective tools for the experimental exploration of the nanoworld, and to push the boundaries of this exploration from a robotics research perspective.

The primary research direction at NanoRobotic Systems Lab (NRS Lab) lies in this emerging interdisciplinary field. The field of nanorobotics brings together several disciplines, including nanofabrication processes used for producing nanoscale robots, nanoactuators, nanosensors, and physical modeling at nano scales. Nanorobotic systems emphasize the engineering aspect of nanorobotics and include the manufacturing and application technologies of nanorobotic manipulation systems, nanoelectromechanical systems (NEMS), and nanorobots (nano-sized robots, which have yet to be realized). NEMS will serve as both the tools to be used for fabricating future nanorobots as well as the components from which these nanorobots may be developed. At present, nanorobotic manipulation and assembly are one of the main approaches for building and characterization of NEMS.

Our current projects focus on high resolution nanorobotic manipulation inside transmission electron microscopes (TEMs), nanorobotic systems on a tip, atomic scale mass transport (Fig. 1), intelligent end-effectors for nanorobotic manipulation, and NEMS based on shell engineered carbon nanotubes (CNTs), helical nanobelts, and peapod nanowires. Targeted application fields include nanomaterial science, bionanotechnology, and nanoelectronics.

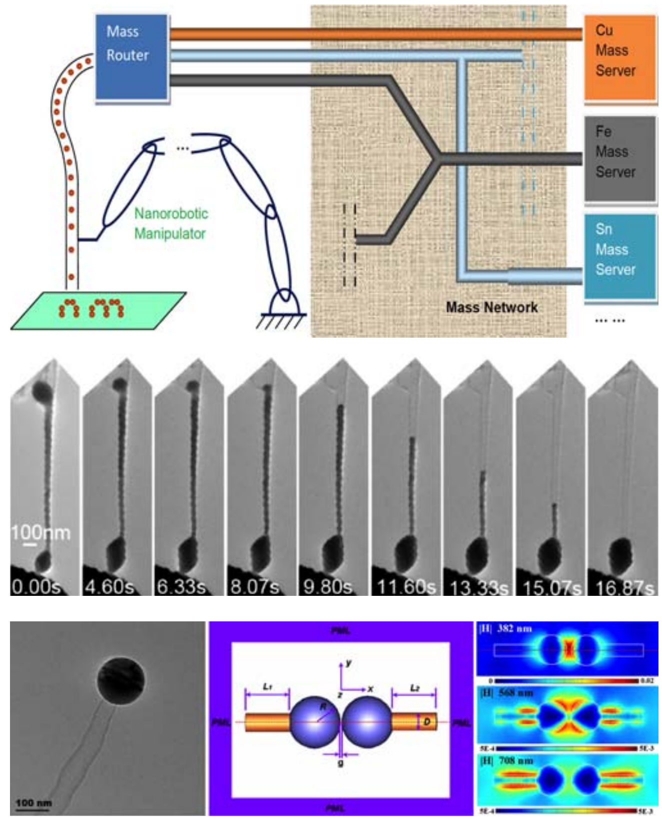

FIGURE 1. Mass transport for additive nanomanufacturing. *Top:* mass network; *center:* attogram mass transport using a metal-filled CNT for 3D additive nanomanufacturing; *bottom:* optical antennas based-on pairs of sphere-on-pillar nanostructures.

Mass transport within, from, and between nanochannels is a promising approach for continuously feeding small numbers of atoms in a controllable fashion and it does not appear that a theoretical limit exists that keeps this from being extended to individual atoms. Combining this feeding technique with a positioning mechanism, e.g., a nanorobotic manipulator, deposited atoms can be positioned from a continuous source. A fluidic system with multiple channels can serve as a mass network to provide a variety of atoms for positioning and connection. An

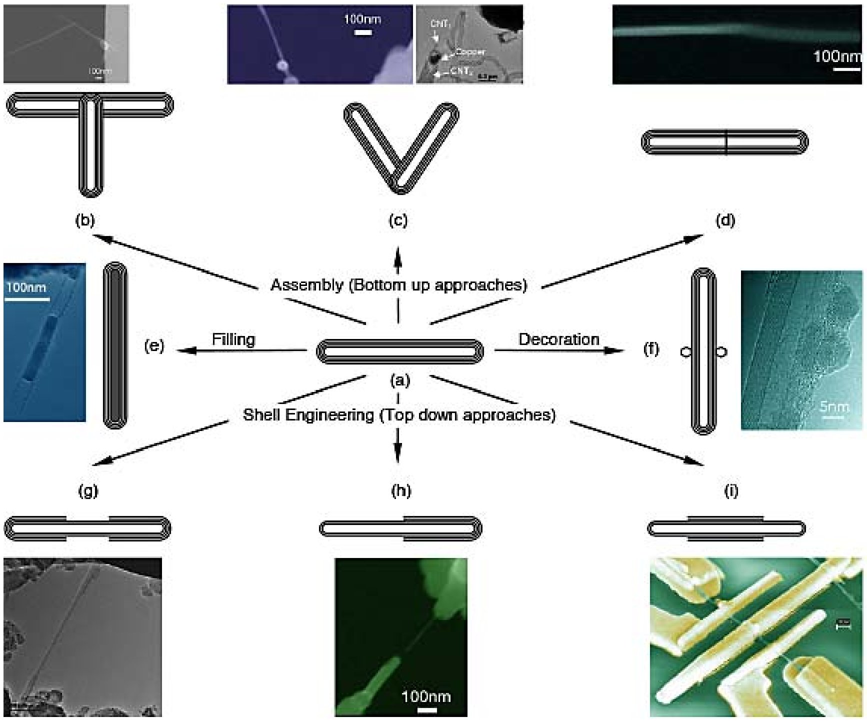

FIGURE 2. Engineering CNTs for nanorobotic systems. Starting from (A) as-grown CNTs, nanostructures can be created by the bottom-up approaches of (B–D) assembling, (E) filling, or (F) decorating them, or in top-down fashion by (G–I) engineering their shells/caps.

example of a manufacturing system is schematically shown in Figure 1 where the mass network resembles the Internet for information. Nanoscale mass networks connect the sources of various atoms to the clients for 3D additive nanomanufacturing. A variety of nanosystems can be enabled with this additive nanomanufacturing technology (As an example, an optical antenna is shown in Fig. 1).

Other building blocks for nanosystems are prepared from nanotubes, nanowires, graphene, rolled-up 3D helical nanostructures such as SiGe/Si and InGaAs/GaAs tubes, coils, rings and spirals. For example, starting from as-grown CNTs (Fig. 2A), building blocks have been created by the bottom-up approaches of assembling (Fig. 2B–D), filling (Fig. 2E), or decorating (Fig. 2F) them, or in a top-down fashion by engineering their shells/caps (Fig. 2G–I). The interconnection of CNTs (Fig. 2B–D) have been realized using van der Waals forces, electron-beam-induced deposition (EBID), spot welding, and mechanochemical bonding. Hybrid approaches towards nanorobotic systems by a combination of nanorobotic manipulation (bottom up) and nanofabrication (top down, e.g., shell engineering of CNTs) feature our research.

ACKNOWLEDGEMENTS

Financial support for the NRS Lab was provided in part by Michigan State University and the National Science Foundation (CAREER: IIS-1054585).

RECENT PUBLICATIONS

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GRADUATE STUDENTS

Zheng Fan, Miao Yu, Chinwe P. Nyenke, Gautham Dharuman

Nonlinear Feedback Control

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Nonlinear feedback control theory has seen remarkable progress in the past few decades. The research group at Michigan State University (MSU) has worked on robust and adaptive control of nonlinear systems for over 25 years. The main emphasis of the research has been on high-gain observers. This is a tool that was invented at MSU and has been advanced over the years by the contributions of 14 PhD and some MS students. Khalil and coworkers have developed the high-gain observer theory in a number of directions, covering stabilization, sliding mode control, regulation, adaptive control, separation principle, logic-based switching, robustness to unmodeled dynamics, sampled data control, effect of measurement noise, disturbance estimation, and connection with Extended Kalman Filter. High-gain observers were experimentally applied to the control of mechanical systems, electric drives and smart-material actuated systems.

Recent Research

Recent research on high-gain observers has focused on three issues:

The first issue is how to modify the observer design to better handle the effect of measurement noise. Because high-gain observers have high bandwidth, they are more sensitive to measurement noise. It was demonstrated that such effects are more dominant during the steady state as opposed to the transient period. This led to ideas to change the observer gain between the transient and steady state periods. Two techniques were investigated, one based on switching the gain [1] while the other uses nonlinearities to change the gain [2].

The second issue is expanding the high-gain observer tool to the so-called extended high-gain observer. This observer estimates disturbance signals in addition to estimating the state variables of the system, which facilitates the compensation for such disturbances and the design of nonlinear feedback controllers that meet performance specifications [3].

The third issue is the design of observers and feedback controllers for nonlinear non-minimum phase systems. Non-minimum phase systems pose a challenge to the design of feedback controllers, even for linear systems. In recent work we have used extended high-gain observers to design feedback controllers for this class of system [4].

Continuing Research

The group continues to work on these issues:

- *Collaborative research* with MSU College of Engineering faculty has provided experimental test beds to validate the theoretical work on nonlinear feedback control. Three areas have been pursued:
- *Electric drives:* In collaboration with Dr. E. Strangas, the group has worked on nonlinear control of induction motors without the use of mechanical sensors (so called sensorless control). New observers were developed and their use in feedback control was justified theoretically [5].
- *Smart material:* In collaboration with Dr. X. Tan, the group has studied nonlinear control of smart material, such as piezo-electric actuators, which are characterized by the presence of hysteresis. High-gain observers in multirate sampled-data control [6] and nonlinear control of nano-positioners have been investigated.
- *Mechanical systems:* In collaboration with Dr. R. Mukherjee, the group has extended the dynamic inversion technique to uncertain nonlinear systems and applied the results to an inverted pendulum on a cart and a helicopter model.

RECOGNITIONS

H. Khalil is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) and International Federation of Automatic Control (IFAC). He received several awards, including the 1989 IEEE-CSS George S. Axelby Outstanding Paper Award, the 2000 AACC Ragazzini Education Award, the 2002 IFAC Control Engineering Textbook Prize, the 2004 AACC Hugo Schuck Best

Paper Award, and the 2009 AGEP Faculty Mentor of the Year Award. At MSU, he received the 1983 Teacher Scholar Award, the 1994 Withrow Distinguished Scholar Award (College of Engineering), the 1995 Distinguished Faculty Award, and was named University Distinguished Professor in 2003.

ACKNOWLEDGEMENT

H. Khalil's research has been funded continuously by the National Science Foundation since 1979. It was also funded by the US Department of Energy and Ford Motor Company.

SELECTED RECENT PUBLICATIONS

J.H. Ahrens and H.K. Khalil. "High-gain observers in the presence of measurement noise: A switched-gain approach." *Automatica*, vol. 45, 936–943, 2009.

A.A. Prasov and H.K. Khalil. "A nonlinear high-gain observer for systems with measurement noise in a feedback control framework." *IEEE Trans. Automat. Contr.*, vol. 58, 569–580, 2013.

L.B. Freidovich and H.K. Khalil. "Performance recovery of feedback-linearization-based designs." *IEEE Trans. Automat. Contr.*, vol. 53, 2324–2334, 2008.

M.S. Nazrulla and H.K. Khalil. "Robust stabilization of non-minimum phase nonlinear systems using extended high gain observers." *IEEE Trans. Automat. Contr.*, vol. 56, 802–813, 2011.

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J.H. Ahrens and X. Tan and H.K. Khalil. "Multirate sampled-data output feedback control with application to smart material actuated systems." *IEEE Trans. Automat. Contr.*, vol. 54, 2518–2529, 2009.

Energy Reliability and Security Laboratory

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Research Mission

The ERISE Laboratory is engaged in the development of innovative systemic approaches to facilitating secure and reliable energy delivery solutions. These systemic approaches integrate system architectures, protection, control and communication.

Ongoing Research Projects

ERISE researchers are currently developing several integrative solutions that enable secure and reliable energy delivery. Three of the major projects are described below.

A Lyapunov function based remedial action screening (L-RAS) tool using real-time data

This $1.5 million project is sponsored by the US Department of Energy (DOE) and is led by Prof. Mitra. It significantly advances the state of the art in real-time stability solutions that empower superior decision-making in power system control centers.

Following a disturbance that can potentially destabilize the grid, the system can evolve along any of numerous possible trajectories, which may be exacerbated by subsequent events or ameliorated by operator action. At present, there is no effective tool to assist the operator in making a well-informed choice from amongst a profusion of remedial action alternatives. Using the tools available today, it is impossible to evaluate or screen every trajectory the system could assume—the computational challenge of performing time-domain simulation of every, or even a selected set of probable trajec-tories, within the time available to an operator, is simply unassailable. ERISE researchers are developing a screening tool that uses an approach based on Lyapunov functions to enable, without time-domain simulation, the selection of appropriate remedial actions that are most likely to result in stabilizing trajectories. If necessary, these trajectories may then be quickly evaluated using existing simulation tools. Even during the process of screening and evaluation of remedial actions, the system would be dynamically evolving, so the tool will be continuously updated using real-time data from the SCADA (supervisory control and data acquisition) system.

The L-RAS will also represent a significant mathematical innovation toward enabling the understanding of catastrophic failures in power systems and the rapid and correct selection of remedial actions. The project team includes ERISE researchers and collaborators from the University of Illinois–Chicago, the Center for Advanced Power Systems at Florida State University, Los Alamos National Laboratory, and Southern California Edison.

Transformerless unified power flow controller for wind and solar power transmission

This $2.4 million project is sponsored by the Advanced Research Projects Agency–Energy (ARPA-E). Prof. Fang Peng, Director of the ZELRI Power Electronics Lab at MSU is lead investigator and Prof. Mitra, Director of the ERISE Lab, is co-investigator. This development will lead to a smaller, lighter, and more economical alternative to traditional unified power flow controllers (UPFC).

UPFCs play an important role in modern power systems, with a wide range of applications from facilitating the integration of renewable resources to relieving transmission system congestion. The development of a smaller, lighter and cheaper UPFC will pave the way for more widespread deployment of grid control devices, leading to increased reliability and efficiency in the power grid.

While ZELRI researchers are engaged in the development of the hardware for the transformer-less UPFC, ERISE researchers are working on system integration issues, such as development of advanced models, analysis tools and protection schemes, simulation of use cases and deployment scenarios, and cost-benefit analyses under various deployment options.

FIGURE 1. Graduate students at work in the ERISE lab.

Architecture of resilient microgrids
This body of work comprises several projects, supported by multiple grants from the National Science Foundation and Sandia National Laboratories. It concerns the development of reliable topologies and microsource deployment strategies, robust and autonomous control strategies, and an integrated framework for control and protection of microgrids.

A microgrid is basically a small power system with embedded generation; often it also includes storage capability. It can be a part of the grid, such as a distribution system or part thereof, with distributed energy resources; or it can be a standalone system, such as an island system, a military base, or a shipboard system. Microgrids are diverse in topology, resources, and requirements. In a majority of applications, microgrids are required to meet reliability (dependability) specifications or at least enhance system reliability; often, resilience, i.e., robustness in the presence of disruptive forces, is an added requirement, such as in military microgrids or naval systems.

ERISE researchers have been developing methods for optimal network configuration in microgrids, optimal sizing and location of distributed resources within microgrids, distributed analytics for robust operation of microgrids, multi-agent system based autonomous control architectures, observer-based sensing and protection systems, and integrated protection and control platforms for resilient microgrids.

Other Research Problems

Other research problems being investigated by ERISE researchers include grid-scale storage scavenging to assist renewable energy integration, reliability modeling of clusters of resources, and identification of catastrophic failure modes in power systems.

LABORATORY LOCATION

The ERISE Lab is located in the Engineering Research Complex, Room C-24B. The street address is 1439 Engineering Research Ct, East Lansing, MI 48824. Please call (517) 353-8528 to arrange a visit.

ERISE TEAM

Prof. Joydeep Mitra (Director), Salem A. A. El-Saiah (PhD), Niannian Cai (PhD), Mohammed Ben-Idris (PhD), Nga Nguyen (PhD), Samer Sulaeman (PhD), Lauren Brownridge (MS), Kunal Verma (MS), Elicia Sashington (MS), Valdama Johnson (MS), Yuting Tian (MS), Khaleel O. Khadedah (MS)

Three-Dimension Vision Laboratory

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The 3D Vision Lab explores the boundaries of computer vision in a dynamically changing three-dimensional world. It asks: How can we estimate properties of moving and stationary objects in the world given inherent ambiguities, noise, and resolution limits of our sensors? A variety of two and three dimensional sensors are employed, as well as fusion of the sensors. The problems being addressed include the following.

Vehicle detection and tracking with LIDAR

Autonomous vehicles of the future will require precise sensing of the world around them if they are to navigate through traffic and around parked vehicles, pedestrians and other complex objects. LIDAR is a promising sensor and provides precise 3D point clouds of the environment around a vehicle. This project seeks to build a dynamic world model around a vehicle from an onboard scanning LIDAR.

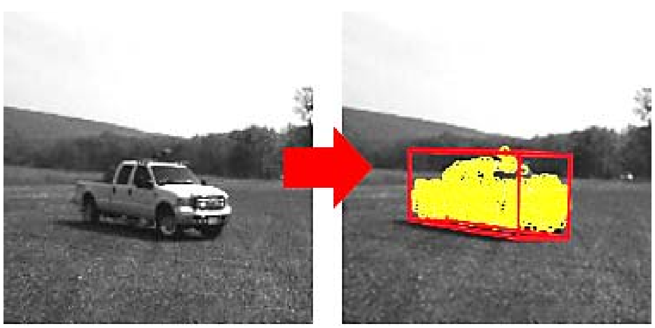

FIGURE 1. 3D LIDAR points on a nearby vehicle enable automatic vehicle pose estimation.

Tasks include identifying what is ground, where is the road, where are objects, and identifying the object type (such as vehicle, pedestrian, curb, etc.). For nearby vehicles we need to track their position and pose and predict their possible future trajectories. To achieve this we fit an adaptive appearance model that enables rapid detection in a point-cloud as well as pose estimation. These detections are resolved temporally through multi-model kinematic tracking.

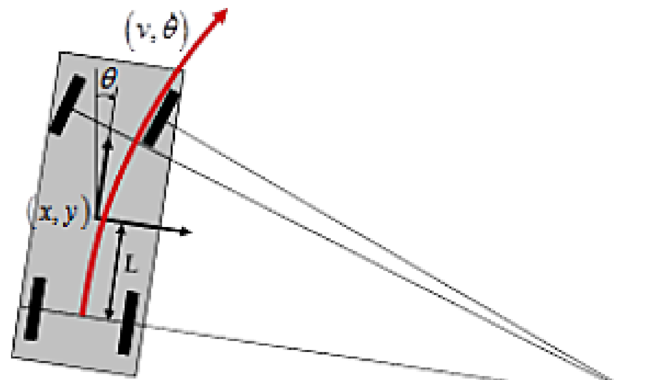

FIGURE 2. Kinematic models enable precise nearby vehicle tracking and trajectory prediction.

Object classification using LIDAR

While range measurements from LIDAR are precise, they are sparse at long range. As a result determining object shape and category can be difficult. We develop 3D shape-based object categorization methods to classify object types at long range.

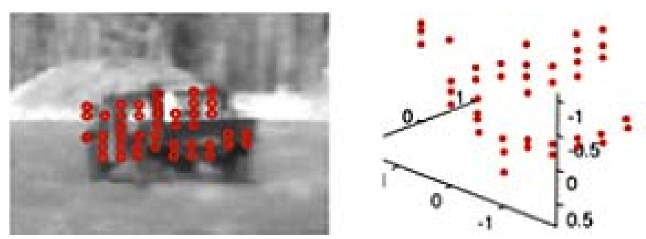

FIGURE 3. LIDAR hits on long-range targets are sparse and are more difficult for object recognition.

Water surface estimation from video

Inherent geometric ambiguities make estimating water surface from video a challenging problem. We are developing methods to resolve these ambiguities and recover the water surface.

Information-based object classification

Object classification can be seen through the lens of information filtering. We use these concepts to do pedestrian and vehicle detection in video that automatically adapts to changing environments.

FIGURE 4. Illustration of vehicle and pedestrian detection in video.

Plant photosynthesis measurement

Limited arable land and high energy costs for cultivation mean that improving plant efficiency and robustness is much needed. But to develop new hybrids requires careful measurement and evaluation of both current and experimental crop varieties. In particular it is important to measure how efficient they are at photosynthesis. Work is beginning with MSU's Plant Biology Lab to create new photosynthesis sensing methods.

FIGURE 5. Improving crop efficiency can lead to large economic gain.

Power Electronics and Motor Drives Laboratory

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The Power Electronics and Motor Drives Lab consists of a low-voltage (three-phase 480 V) lab and a medium- voltage (three-phase 6,000 V) lab for conducting research, development, and testing of power converters/ inverters and motor drives from a fraction of kVA to ten MVA. Working collaboratively with government laboratories, industry, and other universities, projects have ranged from small power converters with power less than 1 kW to multilevel inverters up to megawatts, and motor drives.

Research Scope and Areas

- Advanced power conditioning systems for renewable energy sources such as photovoltaic and wind power from one kW to multi-MW systems and grid-connection controls and protections.
- High power density, high temperature, and low cost power converters and inverters for hybrid electric vehicles (HEV), plug-in HEVs, and pure electric vehicles (EVs). (Fig. 1 shows the HEV and chassis dyno lab providing a tool of research, education, and training.)
- High-voltage high-power converter modules and configurations for power system applications such as FACTS devices including static synchronous compensator (STACOM), unified power flow controller (UPFC), etc. (Fig. 2 is an illustration of base modules developed to cover the entire application area from distribution to transmission.)
- MW converters and inverters for large motor drives, battery energy storage, and mass transit systems.
- Advanced power electronics circuit topologies and controls: from intelligent gate drives for MOSFETs and IGBTs to new converter/inverter circuitries, from battery protection/voltage balancing circuits to circuit intelligence for self-healing, diagnosis, and prognosis, from general applications to high temperature and harsh environments.
- New power conversion technology suited for power conditioning of renewable energy sources such as solar and wind power—Z-source converters to achieve buck and boost operation and to overcome the drawbacks of the traditional technology.

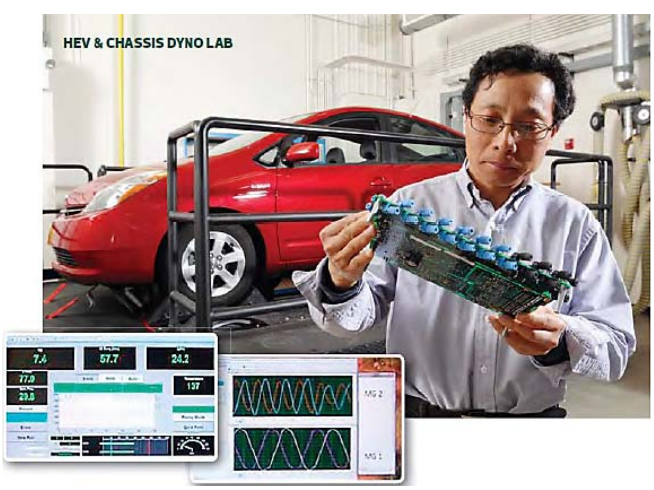

FIGURE 1. HEV and chassis dyno lab.

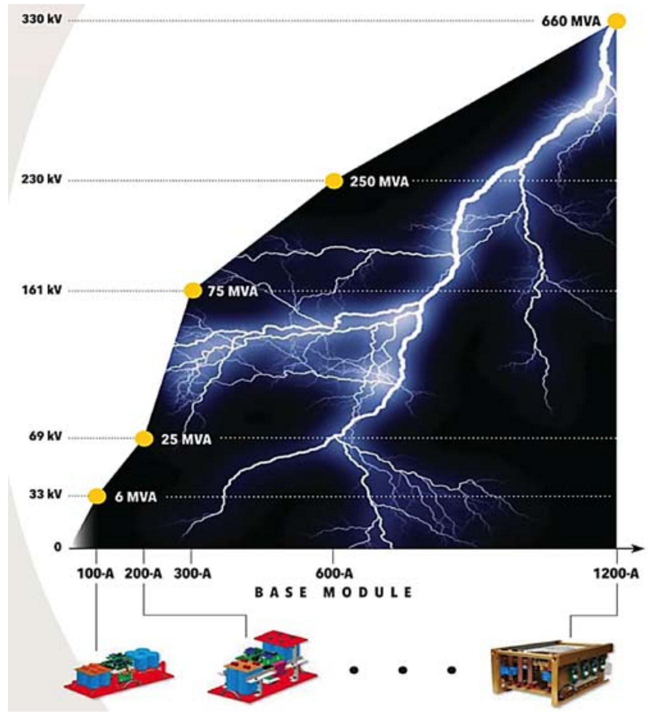

FIGURE 2. Scalability and modularity of high-voltage, high-power converters for power system applications.

Research Results and Highlights

High power converters/inverters have been developed for various applications from large motor drives to power system applications. Many of them have been commercialized. Figs. 3 and 4 show some highlights of the development in the lab.

New multilevel converter/inverter topologies have been developed and demonstrated to achieve high voltage, high power, high efficiency, and high power density. The nX dc-dc converter has demonstrated a 10-time increase in power density.

More than 30 companies, institutes, and government agencies have supported the lab. Fig. 5 shows an on-going project—new transformerless UPFC sponsored by the ARPA-E. Fig. 6 shows an angle view of the main and renewable energy labs.

RECENT PARTIAL PUBLICATIONS

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W. Qian, D. Cao, Cintron-Rivera J.G., Gebben M., Wey D., F. Z. Peng, "A switched-capacitor DC–DC converter with high voltage gain and reduced component rating and count," *IEEE Trans. Ind. Appl.,* vol. 48, no. 4, pp. 1397–1406, July–Aug. 2012.

B. Ge, Q. Lei, W. Qian, F. Z. Peng, "A family of Z-source matrix converters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 35–46, Jan. 2012.

S. Jiang, D. Cao, Y. Li, J. Liu, F. Z. Peng, "Low-THD, fast-transient, and cost-effective synchronous-frame repetitive controller for three-phase UPS inverters," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2994–3005, June 2012.

S. Jiang, D. Cao, Y. Li, F. Z. Peng, "Grid-connected boost-half-bridge photovoltaic microinverter system using repetitive current control and maximum power point tracking," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4711–4722, Nov. 2012.

D. Wang, F. Z. Peng, "Smart gateway grid: a DG-based residential electric power supply system," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2232–2239, Dec. 2012.

FIGURE 3. Development of new converters/inverters.

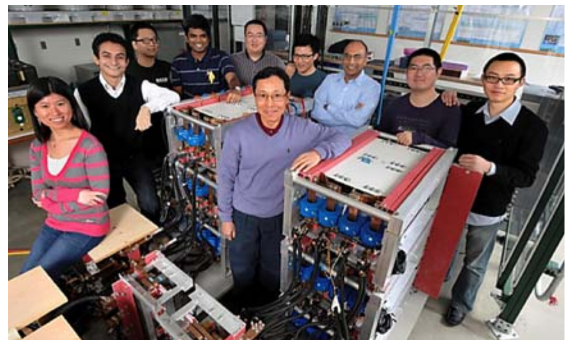

FIGURE 4. 9-MVA inverter system developed in the lab.

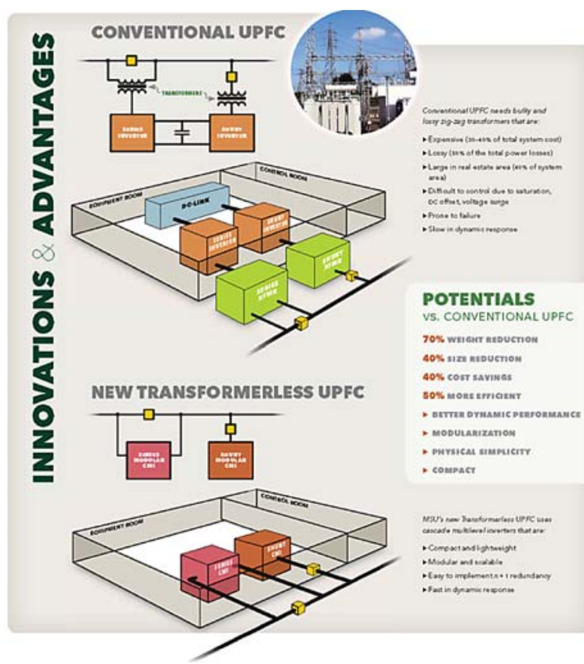

FIGURE 5. Transformerless UPFC.

FIGURE 6. Main (*left*) and Renewable Energy (*right*) labs.

The Electrical Machines and Drives Laboratory

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The Electrical Machines and Drives Laboratory at MSU over the years has collaborated with industry, state and federal government agencies to develop electrical machines, complete electrical drives, and control systems as well as techniques to detect, predict and mitigate faults.

FIGURE 3. PMASynRM totor with ferrite magnets.

Areas of Ongoing Research

Design of electrical machines
These include induction motors, Permanent Magnet AC machines using high magnetic density and ferrite magnet materials. Using numerical methods, lumped parameter models, and analytical techniques, we have designed electrical machines for a hybrid electric vehicle, and designed and built prototypes of new geometries, topologies and materials. We have developed and used in the laboratory testing techniques for these machines.

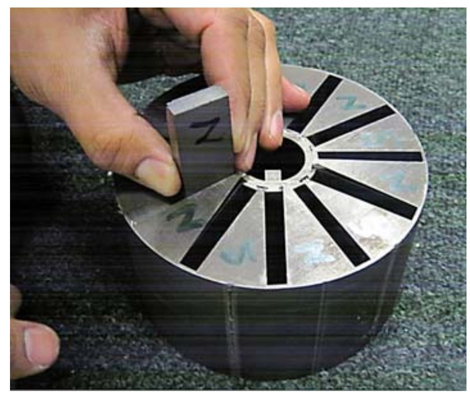


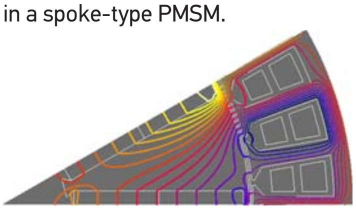
FIGURE 4. Construction of spoke-type PMSMin the lab.

High performance controllers for interior permanent magnet synchronous machines
The laboratory personnel have designed and implemented new control methods for interior permanent magnet motors with the objective to optimize their performance over the complete speed-torque range and applications in electric and hybrid vehicles.

We have implemented these controllers on surface PMAC machines, as well as on large IPM motors (up to 100kW) designed in the laboratory.

Fault diagnosis, prognosis, and reliability for electrical drives
We have been working on this topic for the last 15 years, on applications with high reliability demands, like vehicle power steering starting and traction motors. We have developed techniques utilizing models of the machines, the power electronics and control, and advanced signal processing methods (e.g., time-frequency analysis (e.g., Wavelets, Wigner-Ville, etc.) and categorization and prognosis methods (Linear Discriminant Analysis, hidden Markov models., etc.). Recent work has been on fault prognosis and mitigation. It has been applied to starter motors for ICs and traction motors for HEVs, especially in fractional windings.

FIGURE 1. Magnetic flux lines in a spoke-type PMSM.



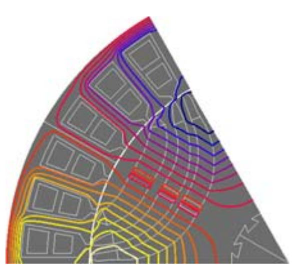


FIGURE 2. Magnetic flux lines in a PMASynRM design.

COLLABORATORS

FACULTY: Hassan Khalil, Selin Aviyente, Fang Z. Peng, Bingsan Wang, Harold Schock, G. Zhu (ME), J.A. Antonino Daviu (Spain), A. Mütze (Austria). GRADUATE STUDENTS: Shanelle Foster, Andrew Babel, Jorge Cintron-Rivera, Reemon Haddad, Eduardo Montalvo, Fang Niu, Cristian Lopez, Rodney Singleton.

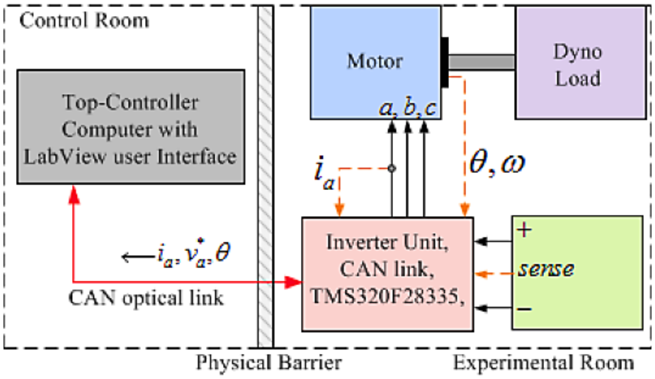


FIGURE 5. Experimental setup for 100kW IPMAC motor.

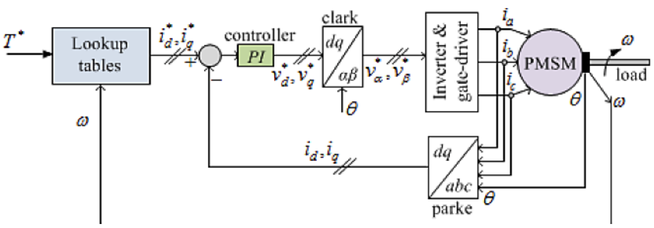


FIGURE 6. Control algorithm using look up and curve-fitting.

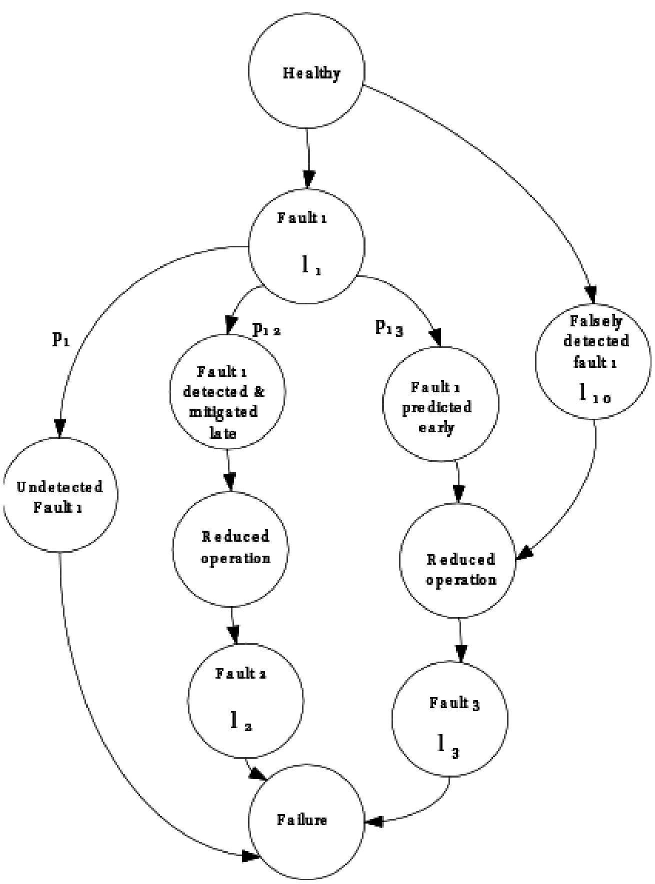


FIGURE 7. Failure paths of a drive under fault mitigation.

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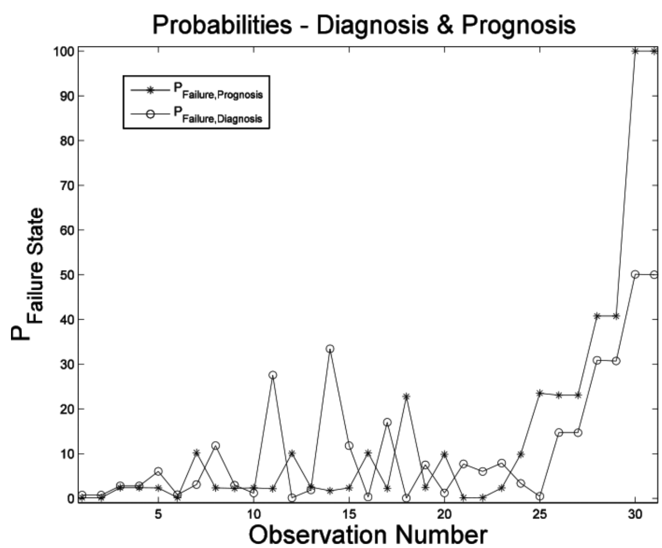

FIGURE 8. Improved drive reliability under failure prognosis.

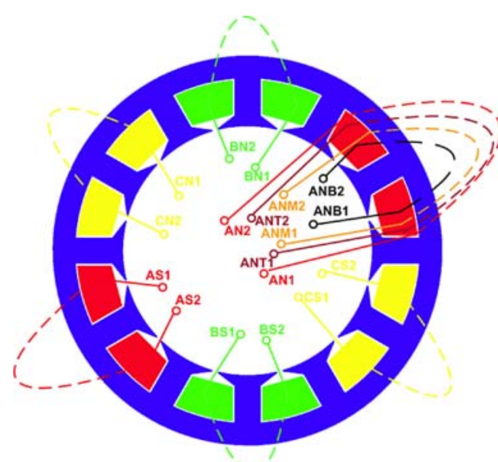

FIGURE 9. Winding diagram for single-layer 2/5 slot/pole/phase fractional slot concentrated winding.

Smart Microsystems Laboratory

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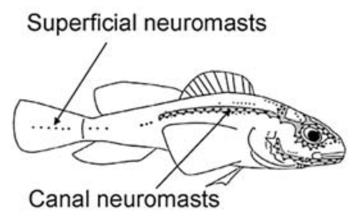
The vision of the Smart Microsystems Laboratory (SML) is to enable smaller, smarter, integrated systems by advancing modeling and control techniques, exploiting insight from biology, and leveraging advances in new materials. Our general research interests span dynamic systems, control, robotics, and smart materials, and our current research is focused on three interrelated areas: (1) modeling and control of novel sensing and actuation materials, (2) bio-inspired robotics, and (3) aquatic mobile sensor networks for environmental monitoring.



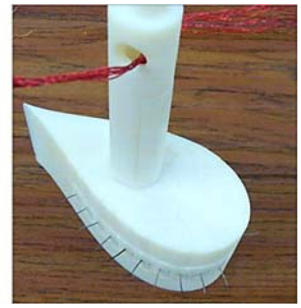


FIGURE 1. (*left*) Illustration of fish lateral line systems for flow sensing (courtesy S. Coombs); (*right*) An IPMC sensor based artificial lateral line system.

Modeling and Control of Novel Sensing and Actuation Materials

Advanced sensing and actuation materials hold strong promise in micro/nano systems, robotics, and biotechnology among others. The development and application of these materials, however, present a myriad of challenges due to nonlinearities, multi-physics coupling, and sophisticated interactions between the materials and other system/environmental components. One area of our interest is the modeling and control of hysteresis, a nonlinearity that is ubiquitously exhibited by smart materials. We are also interested in physics-based and control-oriented dynamic modeling for new materials. For example, we have taken a systems perspective to investigate the modeling, control, and applications of two classes of soft sensing and actuation materials (also known as artificial muscles), ionic polymer-metal composites (IPMCs) and conjugated polymers.

Bio-inspired Robotics

Nature is a rich source of inspiration for robot development. Millions of years of evolution have endowed biological systems with morphological, neurophysiological, and behavioral features that enable them to survive and thrive in their environments. Merging biological insight with advanced materials, fabrication, dynamic modeling, and control theory, we are interested in bio-inspired robotics at all levels from basic sensing and actuation mechanisms, to robot design, and to collective behaviors. For example, Figure 1 shows our use of ionic polymer-metal composite (IPMC) materials for developing artificial lateral line systems for flow sensing in underwater robots and vehicles, and Figure 2 shows several robotic fish prototypes that we have developed.

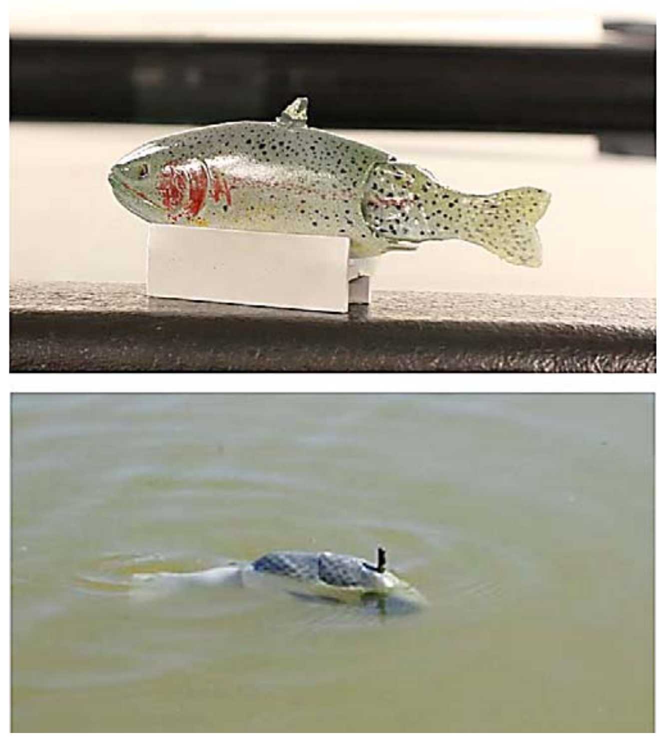


FIGURE 2. Robotic fish prototypes developed by SML.

FIGURE 3. Gliding robotic fish "Grace" developed by SML: (*top, left*) Dimensions and equipped sensors; (*top, right*) the robot demonstrating gliding in a pool; (*bottom*) the robot swimming in the Kalamazoo River and sampling crude oil concentrations.

Aquatic Mobile Sensor Networks for Environmental Monitoring

Monitoring water quality is critical to ensuring the health and safety of aquatic and marine ecosystems. Due to their compact size and low cost, robotic fish hold a strong promise in forming underwater mobile sensor networks for dynamic monitoring of aquatic environments. We have successfully demonstrated a novel type of underwater robots, gliding robotic fish, that merges the energy-efficient feature of an underwater glider and the highly maneuverable feature of a robotic fish, for long-duration monitoring of versatile water environments. See Figure 3. We are currently working with experts in wireless sensor networks, signal processing, environmental engineering, and aquatic ecology, to develop robotic fish-based collaborative sensing solutions for aquatic environments.

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ACKNOWLEDGEMENT

The research of SML has been sponsored by the National Science Foundation (NSF) including the NSF-supported BEACON Center, and the Office of Naval Research.

GROUP MEMBERS

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Electric Power Conversion Laboratory

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The Electric Power Conversion Lab (EPCL) is dedicated to gain fundamental understanding of electric power conversion systems and develop innovative solutions to system reliability and efficiency. The research activities are mainly in the following areas:

- Development of novel power converter topologies that feature high reliability, efficiency
- Modeling, modulation, and control of power electronic systems
- Application of the power converters as grid interface for renewable energy sources
- Application of the power converters in high performance electric drive systems

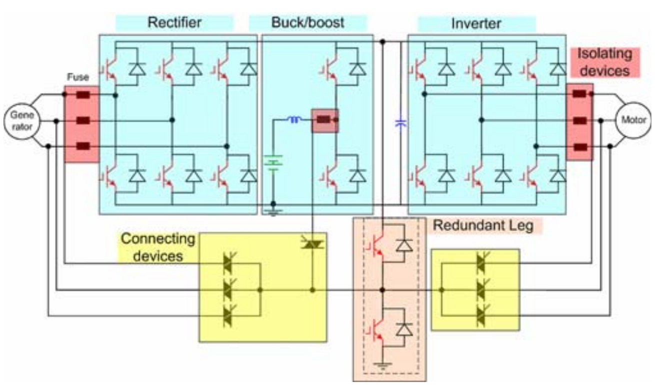

FIGURE 1. Fault tolerant power-train topology.

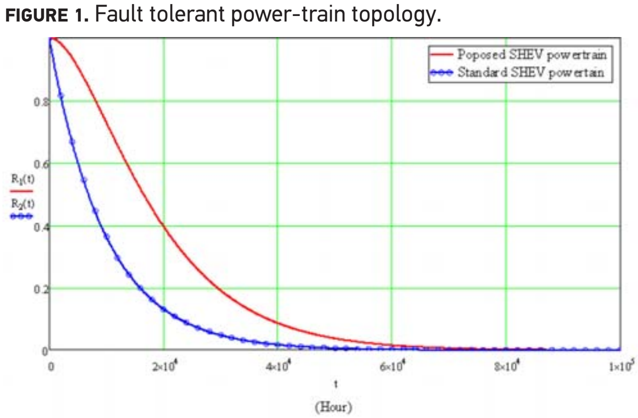

FIGURE 2. Significantly improved reliability compared to standard powertrain.

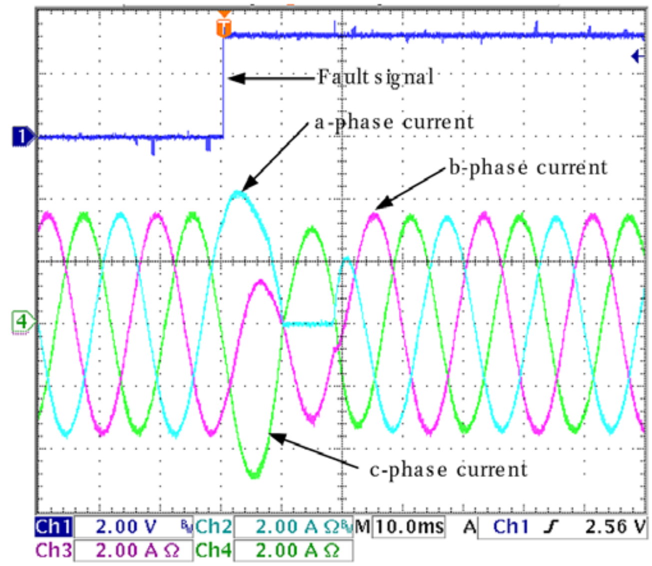

FIGURE 3. Fast detection of and healing from fault events.

The EPCL is equipped with modern experimentation and instrumentation measures. Currently, the following major equipment has been dedicated for research: high-bandwidth digital oscilloscopes, programmable ac and dc electronic load, programmable dc power source, digital signal processor platforms, dSPACE control platform, and high-end personal computers and various simulation software packages.

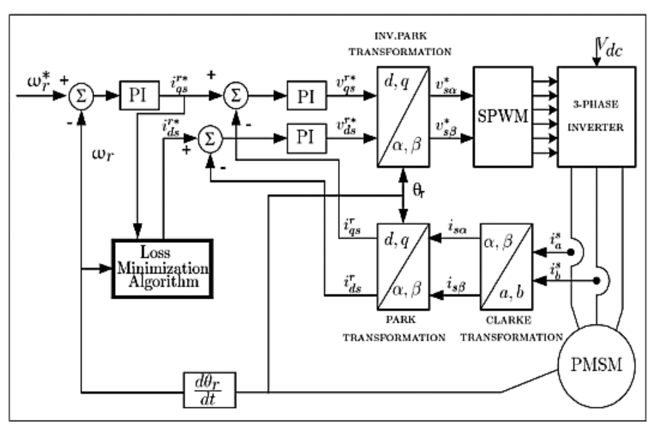

FIGURE 4. Diagram of the efficiency optimized control.

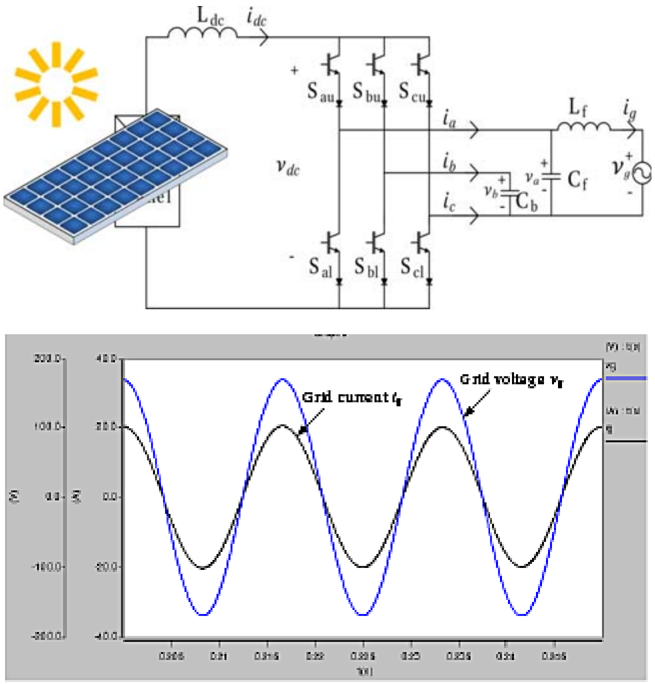

FIGURE 5. Single stage boost solar inverter with reduce-sized dc-link passive component.

High Reliability Powertrain for HEV

A fault tolerant power train topology has been proposed and developed with minimal increased part count. The salient features include:

- Disturbance-free self-healing in case of open-switch and short-switch faults;
- Post-fault operation at the rated power throughput, long-term operation;
- Excellent reliability, doubled MTTF;
- Fast-response and robust fault identification.

Advanced Control of Electric Drives

A combination of analytical and numerical methods that are able to calculate the harmonic losses of permanent magnet synchronous machine (PMSM) at any operating point with less execution time and adequate accuracy.

Effective Solar Energy Interface

- Electrolytic-capacitor-less power stage means higher reliability. Smaller size dc link inductor facilitates integration and lower cost.
- Reduced dc link current ripple improves maximum power point tracking and energy yield.

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UNDERGRADUATE STUDENT: Minjeong Kim

Automotive Controls Laboratory

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The research conducted at ACL focuses on applying model-based control techniques to accurately control engine and hybrid powertrain systems, and other engine subsystems such as the valvetrain system. To support the model-based control development and validation, control-oriented engine models are also developed and implemented in the hardware-in-the-loop simulation environment. ACL research areas also include integrated identification and control of automotive systems, optimal control of hybrid powertrain systems, combustion mode transition control, thermo-electric generator system management, and application of the smart material to automotive systems. Active control of the automotive engine and its subsystems is an essential foundation to realize the new engine technologies possible and research at MSU ranges from new control concept development to validation.

Crank-based real-time engine model [4]

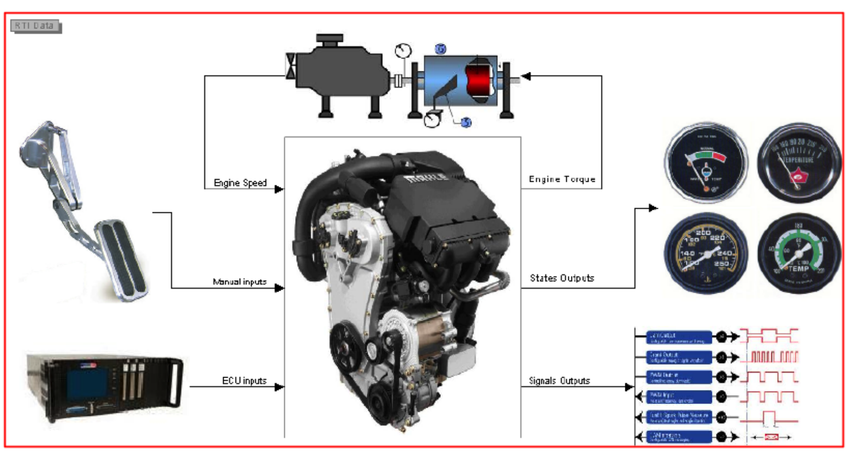
For closed-loop combustion control, in-cylinder pressure and temperature are critical information for the HIL (hardware-in-the-loop) simulations. This real-time engine model uses the mean-value model for intake and exhaust flow dynamics, crank-based combustion model for MFB (mass-fraction-burned), in-cylinder pressure, and temperature signals; and a combustion event-based model for fuel injection, ignition, and engine torques. This engine model is capable of simulating engine combustion modes such as SI (spark ignited), HCCI (homogenous charge compression ignition), and SI-HCCI combustions. This model is implemented in the dSPACE HIL system.

Closed-loop combustion control

A prototype engine controller has been developed for closed loop combustion control utilizing the in-cylinder information, such as pressure and/or ionization, for closed loop combustion control. The developed controller samples the in-cylinder pressure and/or ionization signals every crank degree and calculates engine IMEP (indicated mean effective pressure), MBT (minimal advance for the best torque), MFB, and SOC (start of combustion) in real-time. These calculated engine variables are used for closed loop combustion control of engine MBT timing, combustion stability, EGR rate, and combustion mode transition.

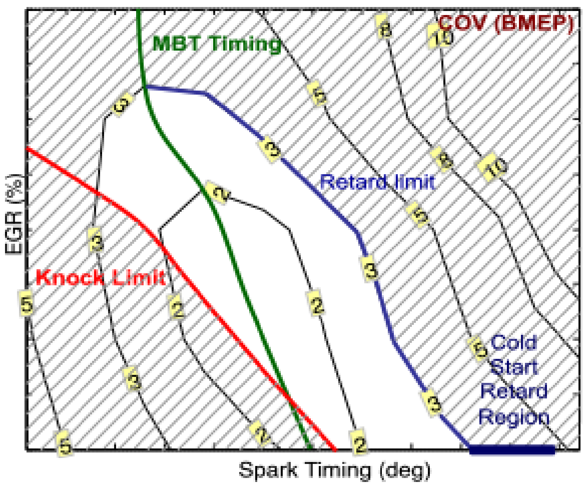
SI and HCCI combustion mode transition control [1]

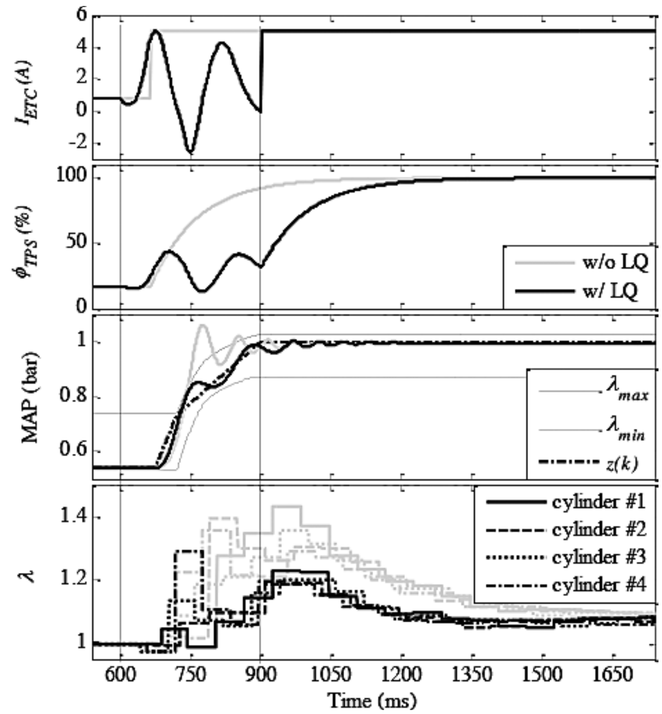
The SI and HCCI mode transition control utilizes two-step valve lift and electrical cam phasing systems. With the help of the hybrid (SI-HCCI) combustion mode during mode transition, the LQ (linear quadratic) optimal throttle and iterative fueling controls provide smooth combustion mode transition between SI and HCCI combustion.



Biofuel lean NO_x trap (LNT) regeneration control

This research integrates the on-line adaptive biofuel content detection and closed loop AFR (air-to-fuel ratio) tracking control during the LNT regeneration. The stability of the adaptive control system during the steady state and biofuel content transition operations is guaranteed. Gain-scheduling control is used to improve the system performance.



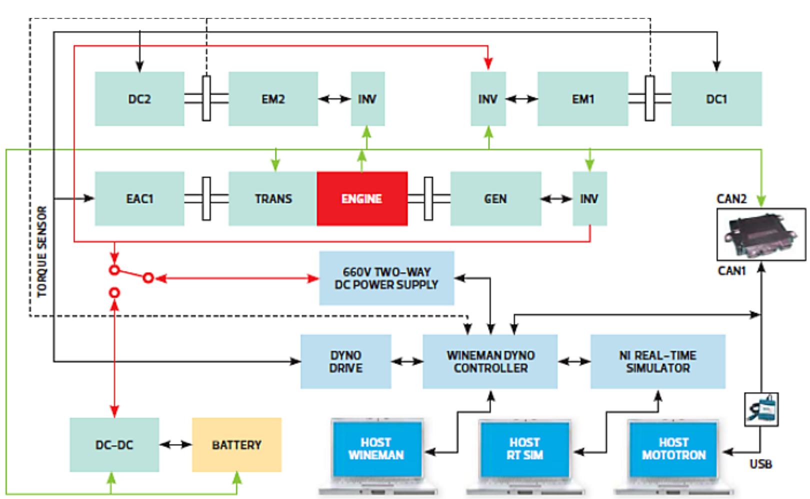


Hybrid supervisory control and HIL simulation of hybrid powertrains

The hybrid powertrain is optimized by real-time optimization algorithms to coordinate subsystems such as engine, electrical machines, generator, battery, and so on. The supervisory control strategies are developed and validated in MSU powertrain in the loop simulation environment.

Other control-related research

- Robust gain-scheduling control
- Gain-scheduling AFR control
- Gain-scheduling hydraulic and electrical variable valve timing control
- Constrained LPV optimal control [3]
- Smart fuel content detection
- IMPC (ionic polymer-metal composite) fuel content detection [2]
- Flow media property (viscosity) sensing



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GROUP MEMBERS

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Electromagnetics, Electronic Materials and Devices, MEMS, and Plasma

Electromagnetics Group: Electronic Materials & Devices

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The investigation of electronic materials and devices is the focus of this research area. Specific topics include computational methods for addressing electro-thermal effects in device design and non-linearity parameter extraction, the associated prediction of failure acceleration in millimeter-wave (30–300 GHz) monolithic integrated circuit power amplifiers, and the operation of devices under extreme electromagnetic, operating frequency, and total power dissipation conditions. This document describes work led by John Albrecht. EMRG group members collaborate widely, and most projects overlap among the domains.

Electron-Phonon Transport

Despite many decades of research and development of semiconductor device design tools, particle simulations that treat thermal transport (phonons) on the same fundamental footing with charge carriers (electrons and holes) do not exist and are not available in the core engineering tool set. Today, devices are simulated by assuming that governing heat equations, which assume the device is continuously in local thermal equilibrium with the crystal lattice, are adequate because thermal diffusion is nearly instantaneous. This assumption is now failing on many fronts. Ideally, the same tools that predict dynamic load-line electronic behavior would provide internal device information regarding the time-dependent generation of heat through the emission and scattering of phonons. The emphasis of this research is to address the basic dynamical issues necessary for the semi-classical tracking of the generation and population transients of lattice vibrational modes internal to semiconductor devices under large signal RF conditions.

Two transistor structures of interest for advanced phonon-electron transport modeling include wide band gap (GaN) RF HEMTs and aggressively scaled InP HBTs operating at THz frequencies. In Fig. 1, an example strategy for mitigating the extreme local thermal conditions present in an HBT is shown. Following typical dimensional scaling arguments, it is possible to expect collector current as large as 100 mA/μm² in future scaling generations under intense investigation [1]. Understanding the generation of heat from charged carriers is critical for predicting associated non-linear effects for practical circuit design.

For the case of the GaN HEMT, the geometry is different, but the local heating is at least as severe. A schematic of the thermal problem for a GaN RF device is shown in Fig. 2. The serious difficulty associated with this geometry is that the hot carrier emission of phonons is predominantly in a small (10nm × 10nm × gate width) region of the channel near the drain end of the gate. Understanding the dynamics associated with large-signal RF operation is important for designing

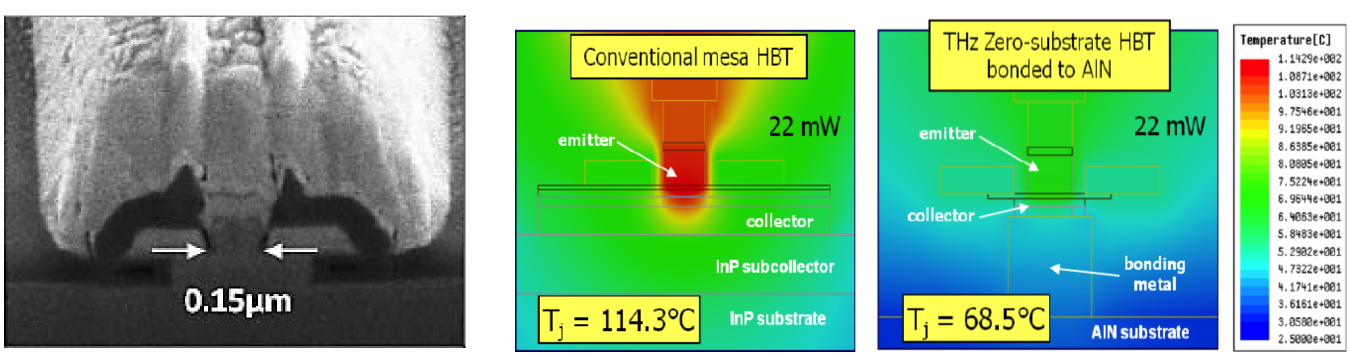

FIGURE 1. Cross-section image of a pre-transferred substrate InP HBT with 0.15µm emitter width and isolated HBT cross-section temperature of substrate removed HBT vs. conventional mesa HBT. Temperature profiles are showing in the color plots. [2]

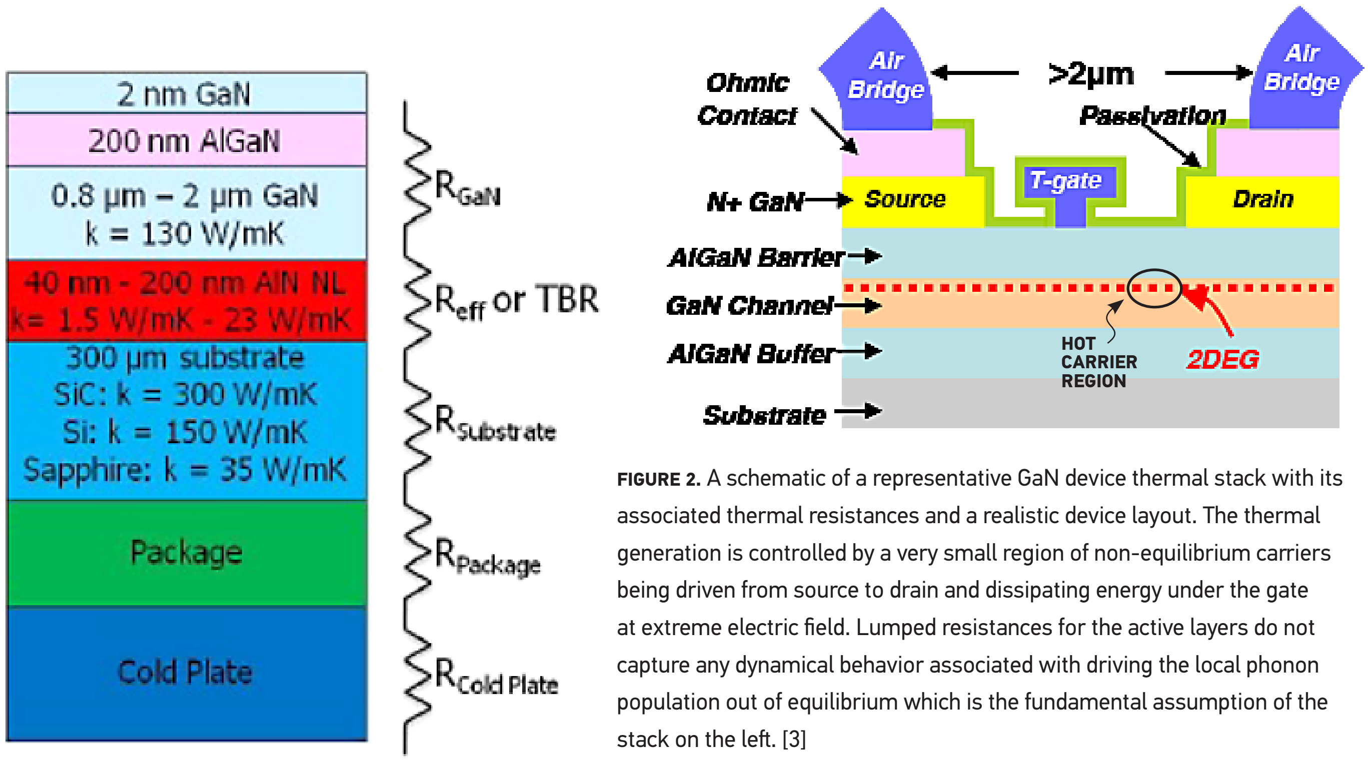

FIGURE 2. A schematic of a representative GaN device thermal stack with its associated thermal resistances and a realistic device layout. The thermal generation is controlled by a very small region of non-equilibrium carriers being driven from source to drain and dissipating energy under the gate at extreme electric field. Lumped resistances for the active layers do not capture any dynamical behavior associated with driving the local phonon population out of equilibrium which is the fundamental assumption of the stack on the left. [3]

reliability test conditions that accelerate the physical conditions that are not inadvertently introducing phenomena that are not present during amplifier operational conditions. It is also critical to understand these thermal drivers as transients in the entire stack shown on the left of Fig. 2 and one objective is to treat the thermal stack starting from the microscopic process of heat generation.

Other Selected Topics

Among other focus areas are the high-field dynamics of electrons and their coupled EM fields in wide band gap channels in vacuum-electronic type configurations, the treatment of non-linear parameter extraction for RF design starting from particle simulation of the Boltzmann Transport Equation, and the treatment of numerically stiff problems associated with particle treatments of minority carriers. One example of this work would be the extraction of X-parameter design data for mm-wave devices under electrical and thermal stresses so that compact models could be predicted even when the collection of data is a severe challenge. This situation occurs often when amplifier classes with sophisticated harmonic terminations are used at very high frequency.

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Micro and Nanotechnology Laboratory

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Research in MANTL includes fabrication of carbon-based single-material BioMEMS and RFMEMS; neural engineering for prosthetics and brain disorders; mind-controlled and wall-climber robots; technology assisted solar-energy systems (TASS); maple-seed robotic fliers (MRF); energy scavenging from static charges; functionalized bricks with embedded intelligence (FBEI) to study dancing, cognitive training and bullying; FBEIs for K–12 outreach, undergraduate and graduate education, and workforce training.

Single Material MEMS (SMM)

As diamond is bio-compatible, the MSU researchers demonstrated MEMS and SMM probe arrays using microcrystalline diamond (MCD) for the first time. Current work focuses on SMM (Fig. 1) and the use of ultrananocrystalline diamond (UNCD) in RFMEMS and in NEA fabrication for applications in (A) communications and (B) neural disorders and prosthetics, respectively.

Diamond Piezoresistive RFMEMS

Due to diamond's highest piezoresistive gauge factor, as demonstrated at MSU for the first time in 1991, RFMEMS with piezoresistive detection were fabricated for the first time by Dean Aslam's group in 2011 (Fig. 2).

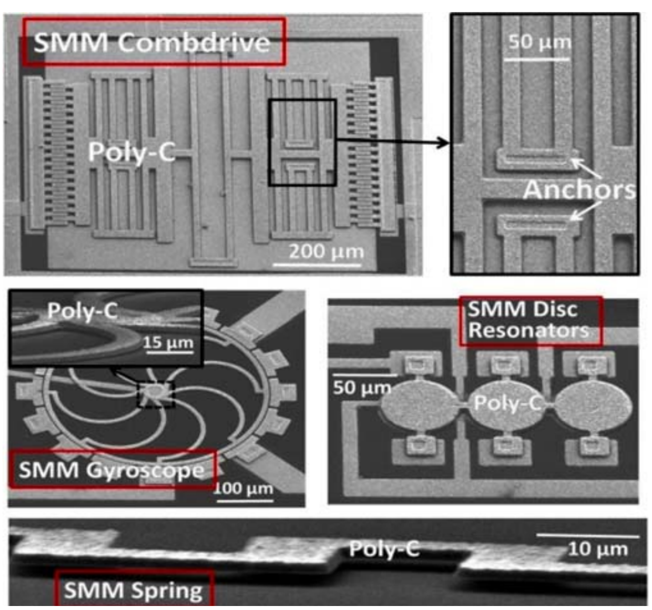

FIGURE 1. Examples of SMM devices.

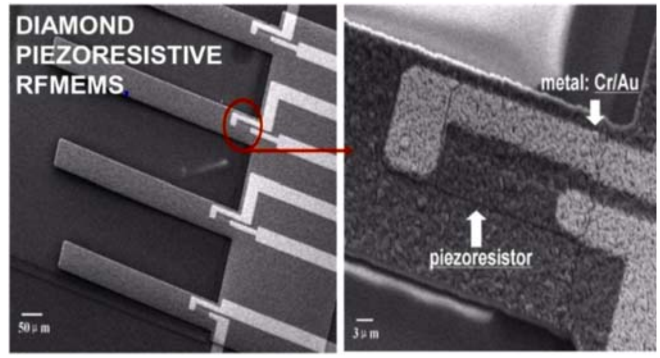

FIGURE 2. Diamond piezoresistive MEMS.

Neural Engineering

Electrical signals, originating from brain, heart and muscles in the human body, are crucial for proper functioning of the body and can be detected by EEG, EKG and EMG devices. In contrast to the conventional use these devices by medical professionals to monitors disorders, recent collaborations between engineers, psychologists and other scientists are leading to monitoring and analyzing a person's sleep patterns, exercise, diet and body parameters (BP, T, heart rate, etc.) to predict individual's happiness and performance at the workplace. The current research in MANTL focuses on design, fabrication and

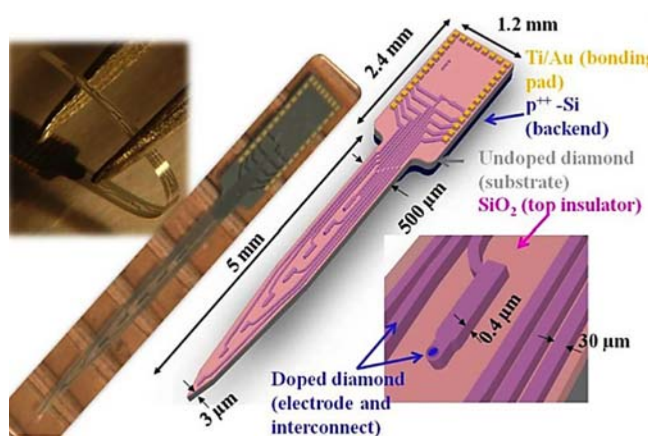

FIGURE 3. Diamond neural probe arrays.

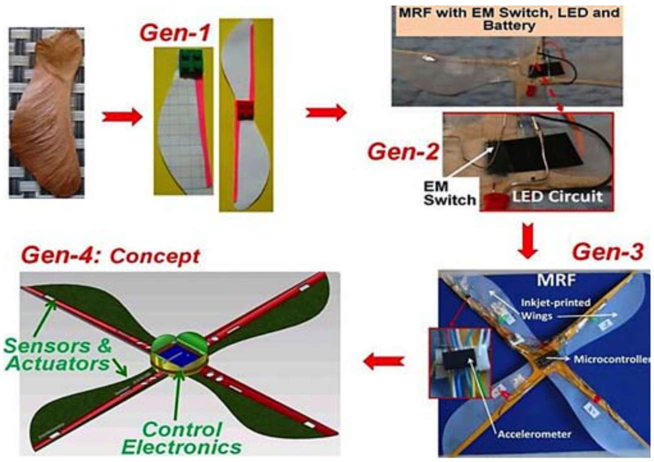

FIGURE 4. Maple-seed robotic fliers.

testing of neural probes (funded by NSF ERC for WIMS during 2000–2010), EEG and EMG for the study of neural disorders, brainwaves, prosthetics and mind- controlled games and robots. Although using MEMS technologies, sophisticated Si-based neural electrode arrays (NEA) have been developed for neural sensing and actuation, drug delivery and cochlear implants, MSU researchers became the first to report MCD based MEMS neural probe arrays for electrical and chemical detection (Fig. 3).

Technology-assisted Smart Solar-systems (TASS)

Using cutting-edge technologies from the market and development of new solar-cell MEMS technologies, next generation solar systems and micro-fabricated solar-powered nightlight devices are being developed in MANTL.

Maple-seed Robotic Fliers (MRF)

Passive maple-seed fliers are being developed for monitoring hard-to-reach and dangerous areas using drone-like remote-linked microfabricated MRF systems (Fig. 4). Although active maple-seed fliers have been developed elsewhere, the passive MRF are unique to MSU.

Fuctionalized Bricks with Embedded Intelligence (FBEI)

While we all know the importance of education, research and entrepreneurship for learners of different backgrounds, the challenge is to find ways to ignite the interest of the learners. FBEIs (Fig. 5), developed at Michigan State during 2000–2010 and funded by NSF ERC for WIMS, have sparked the interest of learners at all levels, K through Ph.D., because they are hands-on and open-design. Additionally, the FBEIs address fundamental science, enabling technologies and system integration and, therefore, are directly connected to cutting edge research projects. A company called Nanobrick was started to market FBEIs.

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GROUP MEMBERS

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ACKNOWLEDGEMENTS

Parts of the above work were supported by Engineering Research Centers Program (ERC) of the National Science Foundation under award number EEC-9986866 during the period of 2000–2010.

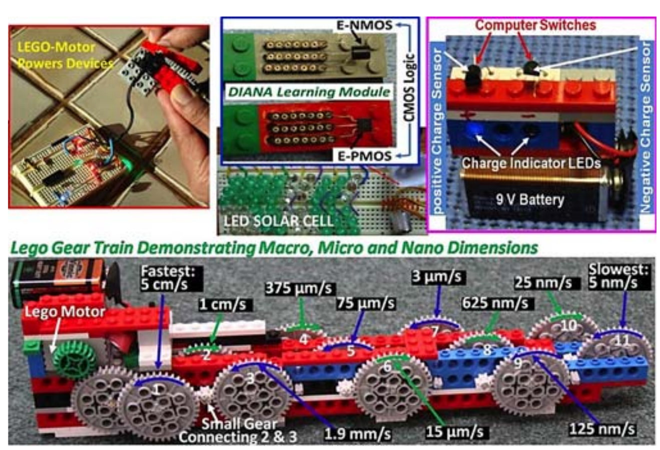

FIGURE 5. Examples of FBEI modules.

Electromagnetics Group: Applied Computational Electroscience

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Developing mathematically rigorous novel, computational methods with provable algorithmic efficiency to solve range of problems in Electroscience is the focus of the ACES group. As will be apparent from the following description, this pursuit relies on advancing three inter-related areas: applied mathematics, applied physics and computer science. In what follows, we shall briefly elucidate some of the recent advances made by our group.

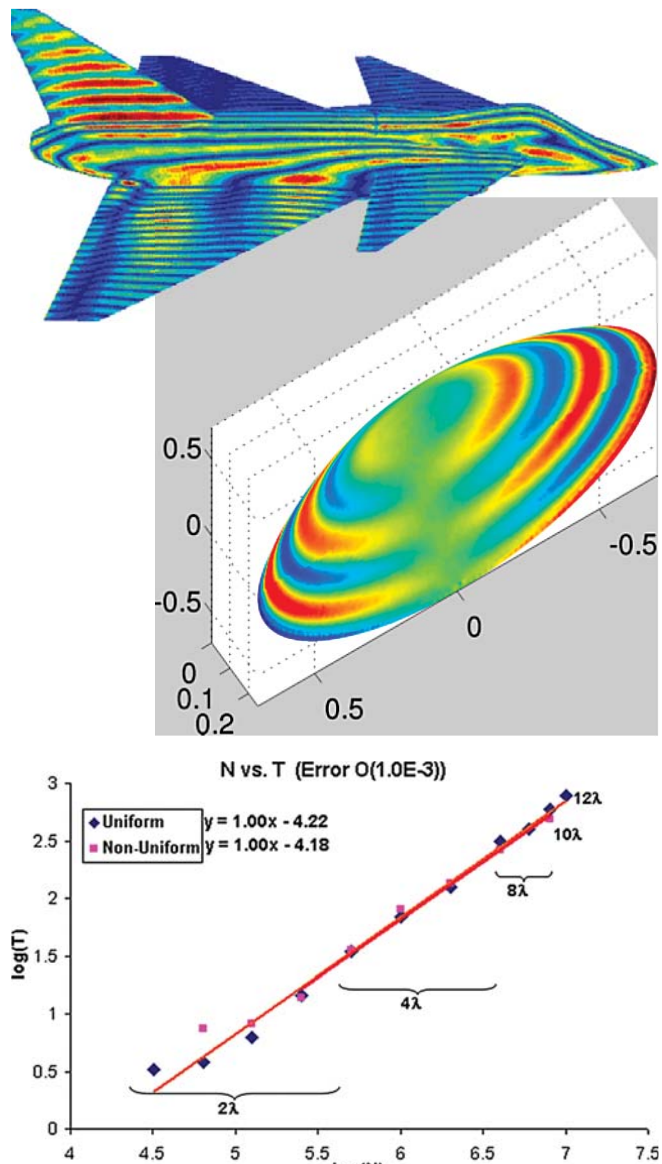

FIGURE 1. Scattering from large structures (64λ aircraft and 20λ reflector antenna) with millions of degrees of freedom and depiction of linear cost scaling algorithms.

Rapid evaluation of Green's kernels for a number of different potentials

Integral equations based analysis methods play a critical role in solution of a number of physical systems ranging from molecular dynamics to astrophysics to electrostatics to electromagnetics. These systems are set up using the appropriate Green's function, and the resulting systems typically scale as $O(N_s^2)$ in both cost and memory complexity. If time is involved, as in the wave equation or diffusion equation, the cost scales as $O(N_t^\alpha N_s^2)$, where N_t and N_s are the number of temporal and spatial degrees of freedom, and $0 \leq \alpha \leq 2$. Over the years, we have developed mathematically rigorous algorithms with provable error bounds that scale as $O(N_s \log^\alpha N_s)$ and $O(N_t \log^\alpha N_t \cdot N_s \log^\alpha N_s)$. These algorithms have been applied to a number of problems ranging from molecular dynamics to acoustics to electromagnetics. Probably scalable parallel algorithms for large multiscale analysis that rely on these methods have also been developed.

Hierarchical geometry and functional framework for integral equation solvers

Integral equation solvers form the backbone of analysis in both acoustics and electromagnetic scattering problems. Open problems with these solvers are two-fold: (i) developing effective means of representing the geometry such that it affords freedom to permit topology optimization and (ii) defining approximation spaces for the unknown quantities. Traditional representation does not permit the flexibility necessary, especially if hierarchical optimization is the end goal. To facilitate these features, we developed a method called the Generalized Method of Moments that relies on underlying partitions of unity on surfaces. At present, we are investigating the rich mathematics of error bounds, complexity, convergence, etc., as well as applying it to challenging problems.

Light-matter interaction

Rigorous quantum mechanical modeling of light-matter interaction is vital to the analysis of numerous processes, ranging from resonant energy transfer in light-harvesting/light-generation applications, to the generation and preservation of entanglement between qubits in quantum information applications. Here, quantum emitters such as molecules, optically active defects, or quantum dots can interact over large distances by way of their mutual coupling to the electromagnetic field. The nature of this second-order interaction is a complex function of the electromagnetic environment. Multiphysics solvers are being used to study Liouville equations describing the dynamics of quantum emitters coupled through the electromagnetic field, wherein the field-mediated interaction parameters can be extracted from classical solutions to the Maxwell equations in realistic material environments. Ongoing work includes development of higher order transparent boundary conditions for the analysis of strong light-matter coupling in high-Q cavities, as well as cavity design and optimization for the generation of maximally entangled states.

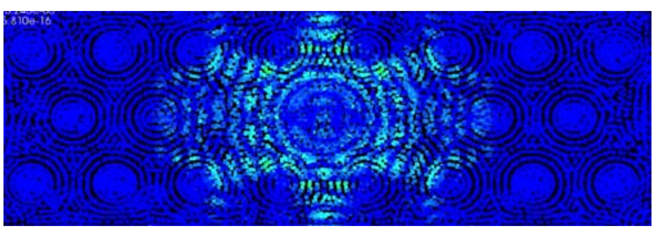

FIGURE 2. Time domain simulations of the EM fields due to a quantum dot coupled to an L3 defect in a GaAs photonic crystal.

Dynamics of Microbubbles

Another intriguing problems that we have recently started investigating is understanding the dynamics of microbubbles. These find several applications ranging from imaging as an ultrasound contrast agent (UCA), microbubble to drug delivery to noninvasive therapy or even in genetic engineering. The fundamental problem is to accurately understand dynamics of microbubbles in the presence of ultrasound. We are actively investigating a series of problems of increasing complexity: single bubble motion, bubble deformation due to pressure, combined bubbles dynamics and ultrasound steering, etc.

Other research

In addition to the aforementioned areas, we have pioneered the development of stable time domain integral equation solvers, a technology that remained an unsolved problem for more than four decades. We have recently made significant inroads into multiscale & multiphysics modeling of plasma-reactors, that include electromagnetics, plasma physics, fluid flows, and heat transfer.

PERSONNEL

COLLABORATORS: E. Rothwell, L. C. Kempel, P. Chahal, C. Piermorocci, Y. Tong, B.Mahanti, H. Lee, J. Albrect. PHD STUDENTS: Jie Lie, Dan Dault (NSF Fellow), Andrew Baczewski (NSF Fellow), Andrew Pray (SMART Fellow), Md. Rashwadeh, Collin Meierbachtol, Steve Hughey. UNDERGRADUATES: Nick Miller, Marco Santia

SUPPORT

AFOSR, AFRL, NSF, GE, NIH

Electromagnetics Group: Terahertz Systems

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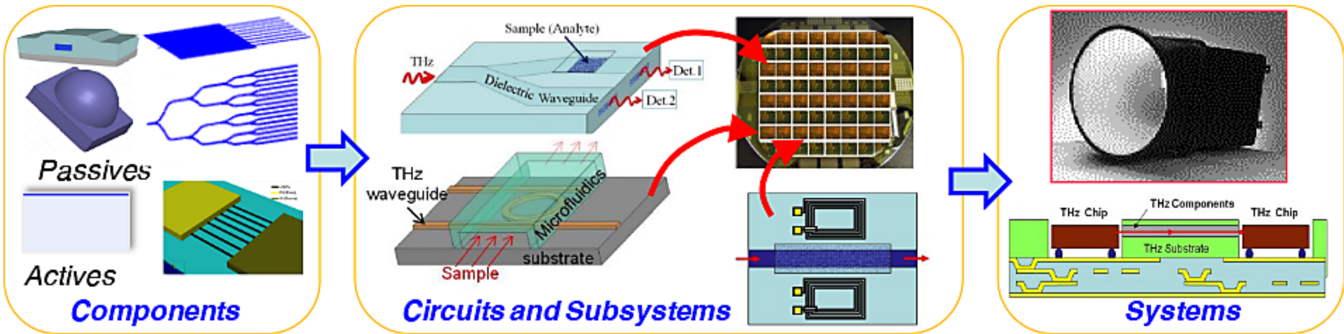

FIGURE 1. Projects in TeSLa range from device level to systems level.

Our research is motivated by the need for efficient and economical high-frequency (millimeter wave and terahertz) components, devices, sensors, and systems. The underlining theme is the use of electromagnetics theory coupled with micro/nanofabrication to design and demonstrate high frequency circuits and sub-systems at the wafer level.

Current projects range in focus from the device level to the systems level. Some of the ongoing projects are as follows:

THz Integrated Devices and Circuits

Realization of terahertz integrated circuits (TICs) is a major challenge. For THz circuits, the device should have cut-off frequencies well beyond 1 THz. Towards this endeavor; TeSLa is developing nanodevices and circuits through the use of nanowires and graphene materials. Example THz devices and circuits are shown in Figure 2. Under a DARPA funded project, the group is developing THz integrated circuits for THz imagers (THz focal plane arrays). Some of the activities carried out by TeSLa within this area include:

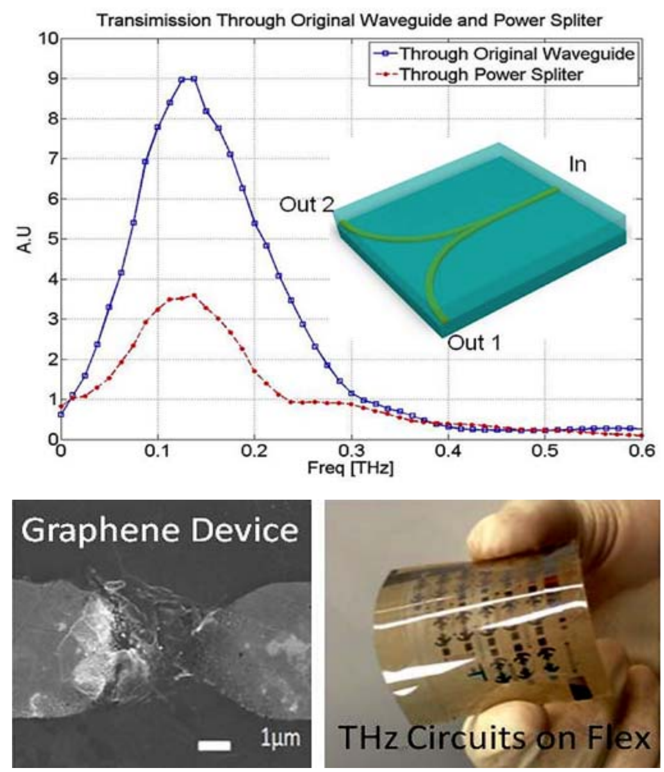

FIGURE 2. Fabricated THz integrated devices and circuits.

- Carbon nano-tube (CNT), III-V nanowires and graphene based devices with ultra-high cut-off frequencies (> 1 THz),
- Heterogeneous integration of different semiconductor devices on Si,
- Development of low-cost high sensitivity THz detector arrays (focal plane arrays),
- THz plasmonic devices and circuits,
- High frequency broad-band modeling and characterization of devices and circuits.

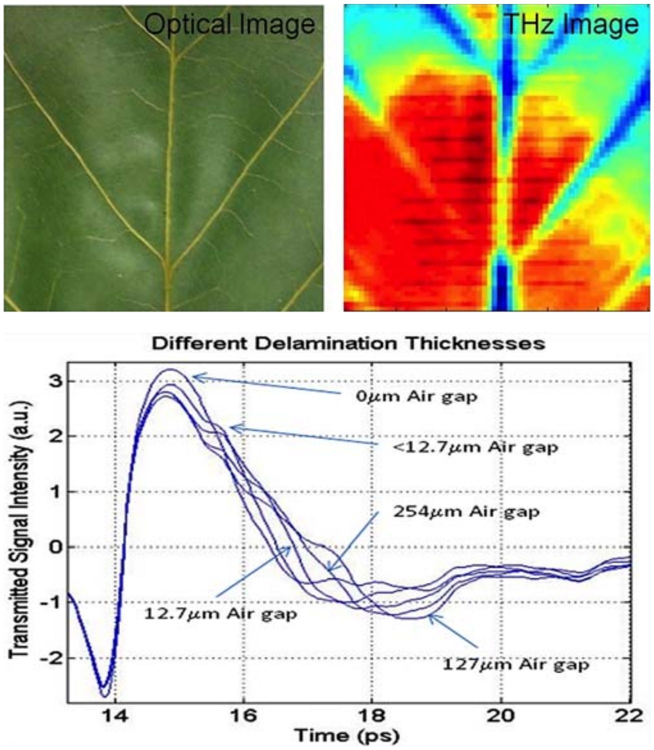

FIGURE 3. NDE and materials characterization in the THz spectral range. *Top:* optical and THz image of a leaf; moisture content can be measured using THz; *bottom:* film delamination (e.g., paint) measurement using time-domain THz.

THz Non-destructive Evaluation (NDE) and THz Material Characterization

With recent advances in light weight plastic and composite structures a vast number of mechanical structures (e.g., automobiles and windmills), THz is finding a niche application in NDE of such structures. This area revolves around the development of techniques in order to examine structures and specimens without putting their integrity at jeopardy using THz radiation. Some of the activities include:

- Developing material characterization techniques of non-conducting substrates,
- Developing methods for 3D objects spectroscopy,
- Imaging for defect or hidden object detection,
- Inspection of specimens for moisture content,
- Developing signal processing algorithms for feature extraction from THz time-domain signals,
- Carrying out sensing studies for chemical and biological applications.

Microwave and Millimeter Wave Circuits and Sensors

Apart from THz circuits and systems, the group is also active in research in the areas of microwave and millimeter circuits and sensors. One of the major focus areas has been in the development of planar active metamaterial circuits and highly sensitive metamaterial inspired sensors. Some of the projects include:

- Microstrip metamaterial phase shifters and tunable antennas (X-band),
- Matamaterial microfluidic sensors,
- Near field probes for NDE,
- Wireless power transfer and energy harvesting circuits,
- Ka-band Leaky wave antennas for fixed frequency beam scanning.

CURRENT SPONSORS

NSF, DARPA, Air Force Research Laboratory (AFRL)

COLLABORATORS

Shanker Balasubramaniam, Leo Kempel, Ed. Rothwell, Steve Shaw, Lalita Udpa. CURRENT STUDENTS: Graduate: Kyoug Park, Xianbo Yang, Joshua Myers, Amanpreet Kaur, Cecilia Acosta, Steve Zajac, Scott Strachan (joint with Prof. Steve Shaw, ME), Jacob Klaser (joint with Prof. Lalita Udpa). UNDERGRADUATE: Jessica Oakes, Jennifer Byford.

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Plasma-Assisted Processing of Materials

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Plasma-Assisted Diamond Synthesis and Processing for Diamond Electronics

The field of diamond synthesis and applications is undergoing a spectacular period of transformation due to advances in the ability to deposit high quality single crystal diamond (SCD). SCD's exceptional semiconductor properties would be transformative and have enormous potential for use in high power electronics technology with applications to transportation, manufacturing, and energy sectors, as well as, for high power, high frequency electronics. For instance, diamond-based power electronics would operate safely at elevated temperatures and would not require the extensive cooling and circuit protection that is found in today's high-power systems. Direct connection of diamond power electronics to the electrical transmission systems of the power grid would facilitate more efficient distribution of alternative energy sources such as wind and solar to the power grid. SCD-based power devices will enable high voltage switching with high efficiency and high current levels.

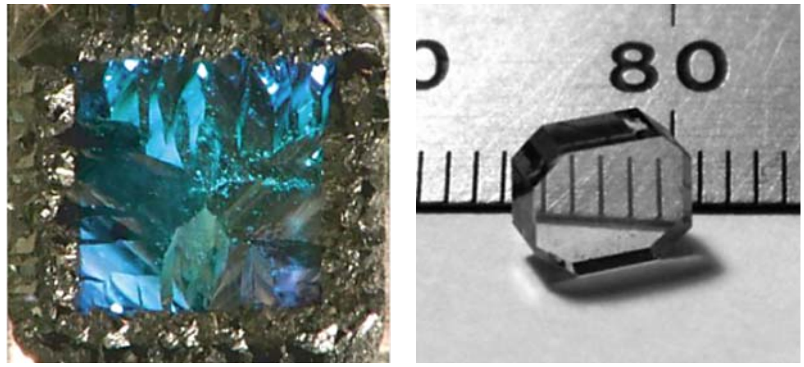

FIGURE 1. Free standing diamond plates. Each plate has been plasma-assisted chemical vapor deposition grown and then was laser cut from the seed substrate. *Left:* Boron-doped diamond with a size of approximately 3mm × 3mm × 2 mm thick. The single crystal boron-doped diamond is blue and a frame of polycrystalline diamond (gray) is around the edge. *Right:* A 1.2 carat diamond plate. The marks on the ruler are in 1 mm increments.

Among the wide bandgap materials, diamond has the best properties for power electronic devices as shown in Table 1 and has the potential to be the next wide bandgap material exploited as SiC and GaN materials reach their theoretical limits.

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap, E_g (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Electric Breakdown Field, E_c (kV/cm)	300	400	2,500	2,200	2,000	10,000
Thermal Conductivity, λ (W/cm × K)	1.5	0.46	4.9	4.9	1.3	22

TABLE 1. Physical characteristics of some semiconductors.

Given the superlative properties of diamond, as applied to several electronic applications, a natural question that arises is why diamond has not seen widespread use. The two bottlenecks that have limited the use of diamond are (1) lack of substrates/wafers of sufficient area size, low cost and high quality for fabrication processes, and (2) lack of shallow acceptors/donors for both p- and n-type semiconductor material doping. Work is underway at MSU to increase the size and quality of diamond substrates. In terms of doping, p-type diamond is readily achieved with boron doping, however boron has a deep acceptor energy level of 0.37 eV. N-type diamond has been a more difficult challenge to solve with the best solution to date being phosphorus with a deep energy level of 0.58 eV. Approaches to dealing with the deep donor and acceptor levels is to (1) utilize heavily doped regions when possible so that the dopant activation energy is reduced giving low resistivity diamond material and/or (2) operate the diamond device at higher temperatures where more dopants are active. The performance of diamond electronics is shown in Fig. 2 as compared to electronics fabricated in SiC and GaN

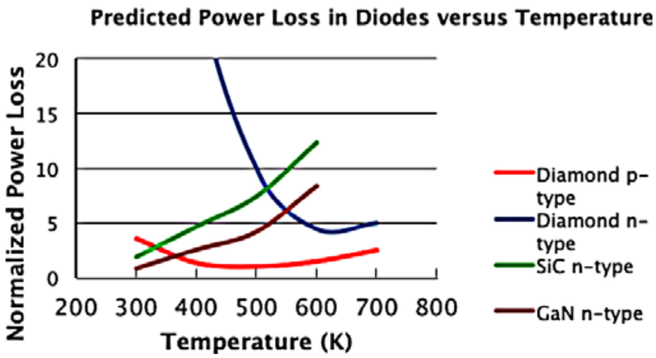

FIGURE 2. Comparison of power loss in diodes of equal breakdown voltage and current flow versus temperature. [T. Grotjohn, Advanced Diamond Science and Technology Topical Conference, Detroit, Oct. 2011.]

materials. Fig. 2 shows that diamond could have superior performance to these other materials at temperatures above 100°C.

The Michigan State University diamond research effort has worked on single crystal diamond for a number of years and has diamond deposition equipment and processes for growing intrinsic, p-type and n-type diamond. Additional processes and equipment are also available for microfabrication of diamond electronic devices such as plasma-assisted etching, laser cutting, polishing and electrical contact formation. A goal of this research is to design, fabricate and characterize high voltage, high power diamond electronic devices including diodes and transistors.

Design of Microplasma Source and Their Applications

Microwave powered plasma sources that produce plasma discharges of less than one millimeter in size are designed and the microplasma discharges are studied. Applications of the microplasma sources to materials processing including deposition, etching and surface treatment are being investigated. Modeling and diagnostics of the plasma discharges is also being done.

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GRADUATE STUDENTS

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Pulsed Laser Deposition & Transport Characterization Laboratory

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FIGURE 1. Pulsed electric current sintering system for densification of thermoelectric materials.

We study electronic materials through synthesis, material characterization, and device fabrication.

- *Material Synthesis:* Pulsed laser deposition (PLD) is used in our lab for thin film deposition, and nanowire growth studies. Solid solution chemistry, powder processing, and pulsed electric current sintering (PECS) is used for the fabrication of bulk samples such as thermoelectric materials, and targets for PLD.
- *Material Characterization:* Bulk and thin film samples are characterized by temperature dependent measurements including electrical conductivity, thermopower, thermal conductivity, Hall effect, current vs. voltage sweeps, and impedance spectroscopy. In addition, room temperature measurements include scanning voltage probes to measure contact resistances, and Raman spectroscopy.
- *Device Fabrication:* Thermoelectric modules have been fabricated for studies of contact resistance, module power output, and module efficiency. Modeling software has been developed for comparison between theory and measured results.

Focused research areas have included thermoelectric materials, oxide-based nanowires, surface enhances Raman spectroscopy (SERS), and doped single crystal diamond.

Thermoelectric Materials

Historically, these materials have been used as power generation devices that convert heat flow into electricity, and have been used in extraterrestrial applications to power spacecraft such as Voyagers I and II, Galileo, and the Mars rover Curiosity. For these high temperature applications, a radio isotope heat source is used for the hot side and radiation into space is used to maintain the temperature of the cold side of the module. Traditional materials have included PbTe, SiGe, and $(AgSbTe_2)_{0.15}(GeTe)_{0.85}$. For terrestrial applications, Bi_2Te_3 compounds have been most commonly used with commercially available products both for power generation and cooling applications. One goal of our research is to investigate new materials that might improve conversion efficiency, or reduce cost of such devices. The efficiency depends on a unitless figure of merit, *ZT*, given by:

$$ZT = \frac{\alpha^2 \sigma}{\kappa} T$$

where α is the thermopower, σ is the electrical conductivity, κ is the thermal conductivity of the sample and T is the temperature in Kelvin. Collaborative research efforts have focused on embedded nanostructuring to improve the *ZT* of these materials, and powder processing techniques to increase sample homogeneity and strength. Through a Department of Energy–Energy Frontier Research Center (DOE-EFRC) located at Michigan State University, over 15 groups from seven institutions across the nation are involved in this effort with expertise spanning first principles calculations through system level integration.

Nanowire Synthesis and Application

The vapor-liquid-solid technique of nanowire synthesis has been used to study the growth of GeO_2 and ZnO nanowires. We have utilized pulsed laser deposition and thermal evaporation techniques for the fabrication of these nanowires. Nanoscale droplets of gold have been used to catalyze the growth of these wires at specific locations on the substrates. Further deposition of gold on the as-grown nanowires has resulted in gold decorated nanowires with droplet sizes in the 3-10 nm scale. We have investigated the use of such random substrates for surface enhanced Raman

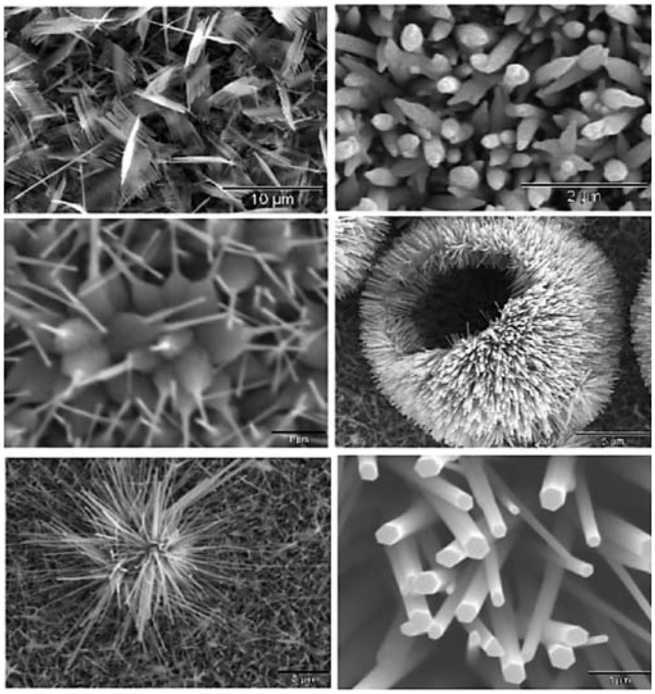

FIGURE 2. Several morphologies of ZnO nanowires grown in our lab.

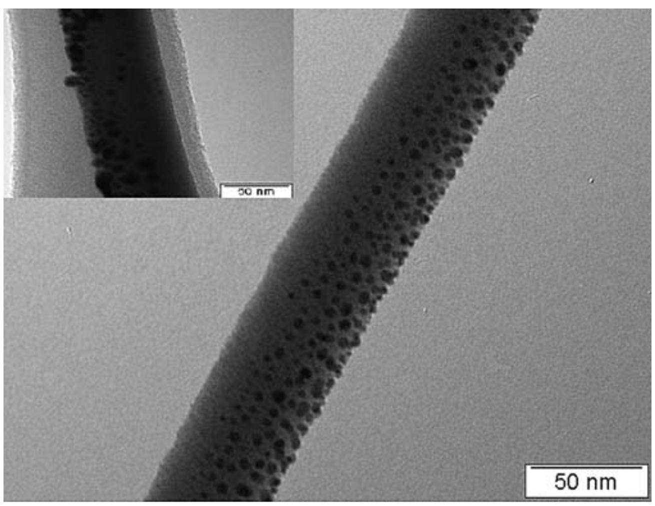

FIGURE 3. Gold decorated GeO_2 nanowires used in surface enhanced Raman spectroscopy studies.

spectroscopy which is an optical detection technique for identifying specific materials. Through such efforts, a simple path to a uniform enhancement of 10^6 in the Raman signal has been discovered. The impetus of this research includes site specific growth of nanowires and sensor development based on the resulting structures.

Diamond

Diamond is a unique material with several exceptional properties, including the highest known hardness, very low friction and adhesion coefficients, unmatched thermal conductivity, high electronic mobility, high melting temperature, high dielectric breakdown, radiation hardness, biocompatibility, and unique chemical inertness. This MSU sponsored research capitalizes on expertise in diamond synthesis, established in the ECE Department, to investigate boron and phosphorus doped single crystal diamond for power electronic applications. Our group is investigating the temperature dependent electrical properties of the as grown samples along with the studies of stable low resistance electrical contacts.

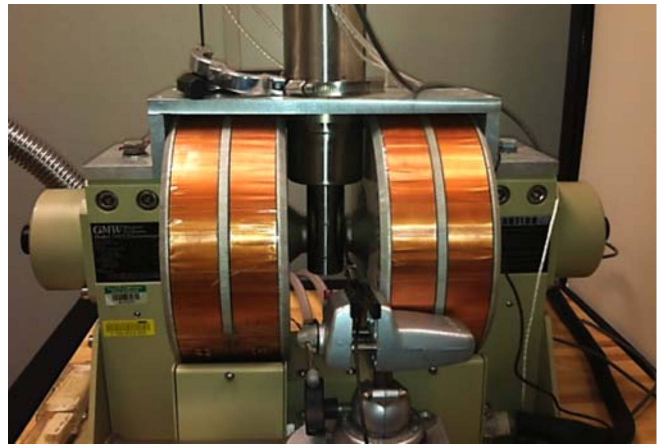

FIGURE 4. Hall effect measurement system sample stage.

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Computational Electromagnetics

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What is Computational Electromagnetics?

Computational electromagnetic as a discipline has its origins in electric power engineering, the oldest and one of the major subdivisions of electrical engineering with signals and systems, electronics, computers and electro-physics.

Power engineers had to compute electric machine inductances and transmission line parameters for which the electromagnetic fields have to be computed – that is, Maxwell's equations describing them have to be solved. It was recognized as a new sub-discipline of power engineering, the original dichotomy having been power systems and electric machinery, to which high voltage engineering and then power electronics were added as they came into being. Field computation was important for insulator stress analysis and even the design of transistors as more and more were packed into smaller areas leading to high electric stress.

Today field computation has gone well beyond power engineering and is a staple of engineers in almost all sub-disciplines of electrical engineering, especially telecommunications (antennas, waveguides, etc.). As engineers deal with systems where electrical engineering interacts with other branches like thermal and fluid systems where too field computation methodologies are developed, coupled systems need to be studied as in, for example, examining how an electrical device heats up. Fig. 1 shows electrical fields interacting with biological systems, lightning radiated electromagnetic fields inducing currents on the fuselage of an aircraft which in turn affects the internal electronics causing low-flying aircraft to crash, and the space shuttle upon re-entry having its dynamics determined by the interaction of mechanical stress, air-flow and heat. In this latter case the coupled system resulted in a matrix equation that was more than 1 million by 1 million in size and we had to rearrange the matrix algorithms to parallelize them to be done on multiple processors. Fig. 2 shows the B-2 bomber's multiple coatings of special paint being designed for thickness to prevent radar reflections so as to make the plane truly stealthy.

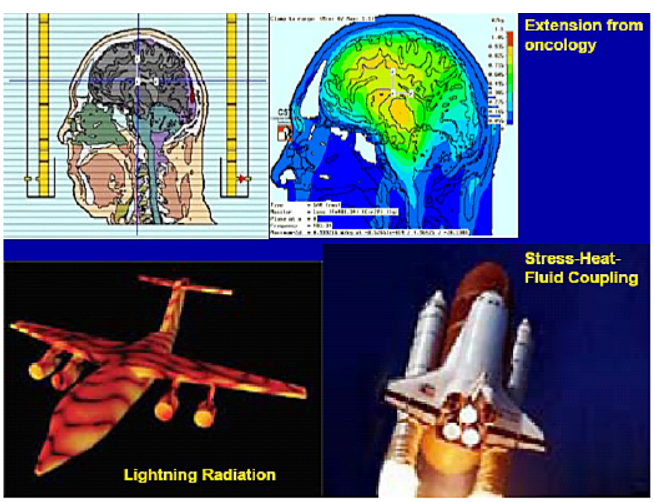


FIGURE 1. Applications of electromagnetic field computation across disciplines.

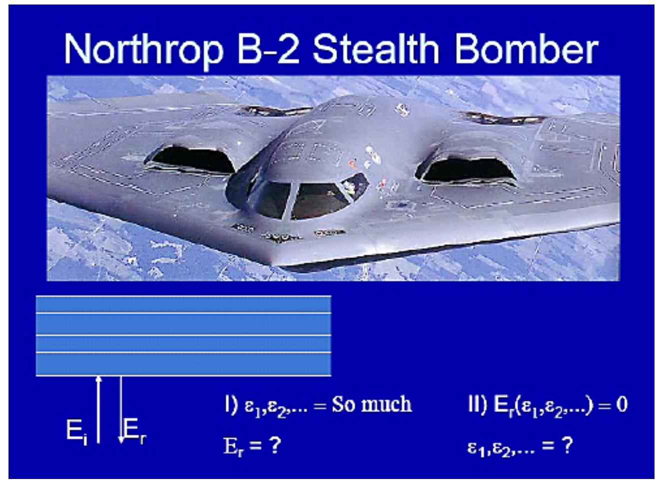


FIGURE 2. Designing surface coats on the B-2 bomber.

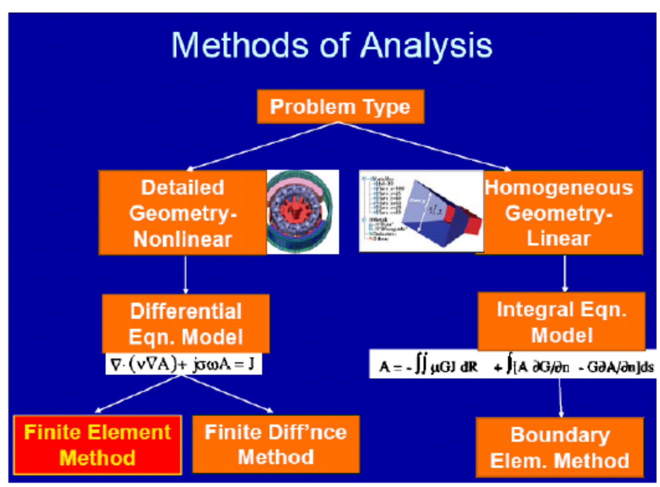
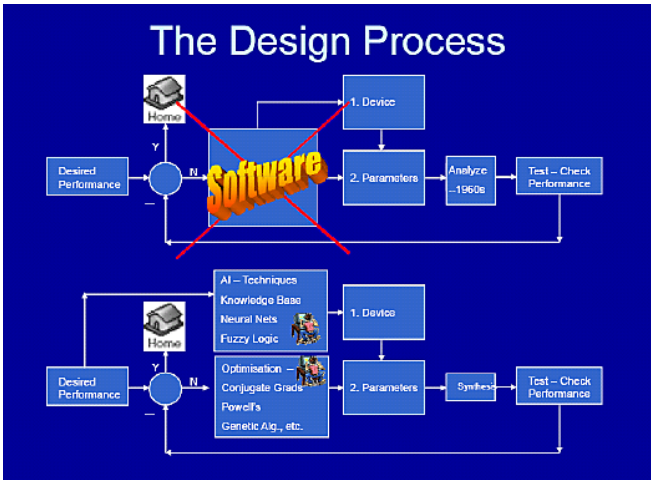


FIGURE 3. Methods and problems.



FUGURE 4. Subject-expert in design: replaced by software.

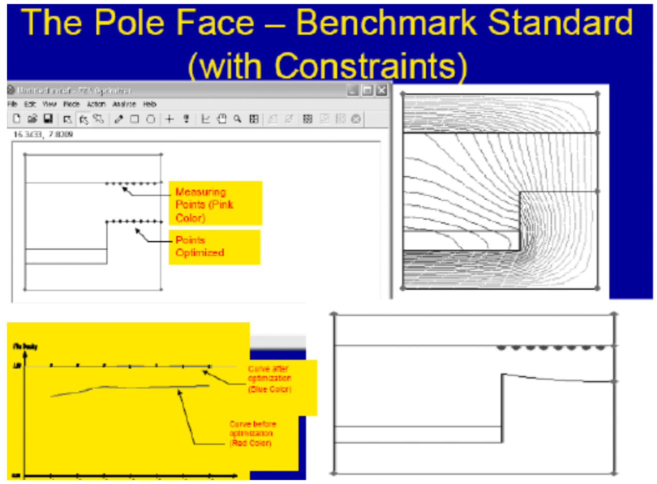


FIGURE 5. Benchmark problem:validating optimization code.

In all these studies the fields may be described by differential equations or alternatively integral equations (Fig. 3). These are approximated to yield linear equations relating the field quantities at various spatial points to each other. Using differential equations is better for devices with detailed geometry as in an electric machine and integral equations for homogeneous systems such as for communication from one antenna to another as in satellite-to-earth communication. Because the methodologies are so different, engineers working with differential equations and engineers dealing with the same equations in integral form see themselves as belonging to different specialties and interact little. Engineering today is so specialized that these two groups often see themselves as different.

Research at MSU

The purpose of this document is describe the several research projects active or planned in this group.

- *Synthesis.* In typical analysis, given the description of a device, we compute its performance. For example, given a coil, we compute its inductance. Real design usually starts with performance and poses the task of synthesizing the device that would yield that performance—the reverse of analysis. We need the coil description to yield the particular inductance value we want. This automated process shown in Fig. 4 with results in Fig. 5 is multi-faceted research and involves various optimization algorithms, artificial intelligence of various types, seamless non-stop mesh generation as the geometry iteratively changes and the incorporation of material characteristic libraries to model materials.
- *Lightning Models*. To the study the drastic effects of direct lightning attachment to aircraft and wind turbines (Fig. 6), the currents in the lightning return stroke need to be modeled and the field radiated therefrom analyzed.
- *Hyperthermia.* In hyperthermia treatment in oncology, kHz range electromagnetic fields are applied to induce eddy current heating in cancerous tissue to heat it. This means determining the exciting coil arrangement to produce the required therapeutic heating profile. It is a coupled optimization problem that is little understood.
- *Parallel Computation on GPUs.* Parallel computation involves rearranging traditional computational processes into separate smaller independent processes that may be implemented simultaneously on multiple processors. Whereas this is well known, recently opportunities have been presented to do the same thing far more cheaply on the graphics processing units of a computer. The programming environment is developing and the algorithms need to be newly reordered.

FIGURE 6. Lightning attachment.

Electromagnetics Group: Applied Antennas and Materials

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The electromagnetic research group consists of four faculty members (Rothwell, Kempel, Balasubramaniam, and Chahal), and carries out a wide variety of research projects spanning the computational, theoretical, and experimental domains. The group comprises approximately 25 graduate and undergraduate students, post docs, and visiting scholars. This document describes work led by Professor Kempel. Note that all group members collaborate widely, and most projects overlap among the domains.

Leaky-wave Antennas

Leaky-wave antennas offer a potentially wide bandwidth (in terms of both VSWR and pattern) near end-fire aperture with high gain. This is in contrast to conventional resonant antennas (such as microstrip patches, wires, and dielectric resonantors) that by their nature are useful over a narrow instantaneous bandwidth and radiate most effectively in the broadside direction. Resonant antennas can be used for near end-fire applications if complex and expensive phase shifters are used; however, even so, phased array antennas suffer from scan-blindness under certain circumstances. Near end-fire apertures with nearly 1 GHz bandwidth in C-band have been designed, simulated, and constructed.

Michigan State University in partnership with the Air Force Research Laboratory and the University of Dayton have developed a number of innovations in leaky-wave antenna design built upon the so-called "half-width leaky-wave antenna." This aperture offers advantages over conventional leaky-wave antennas primarily in construction and feeding networks.

Recent innovations include the use of tunable reactive loads on the open edge of the antenna. This permits tuning of the antenna performance as a function of frequency. The result is unprecidented ability to control the spectral behavior of the antenna to meet design requirements. Traditional leaky-wave antennas steer the beam as a function of frequency. Such antennas have limited applications. As shown in Figure 1, this antenna maintains a consistent main-beam direction across the operational bandwidth.

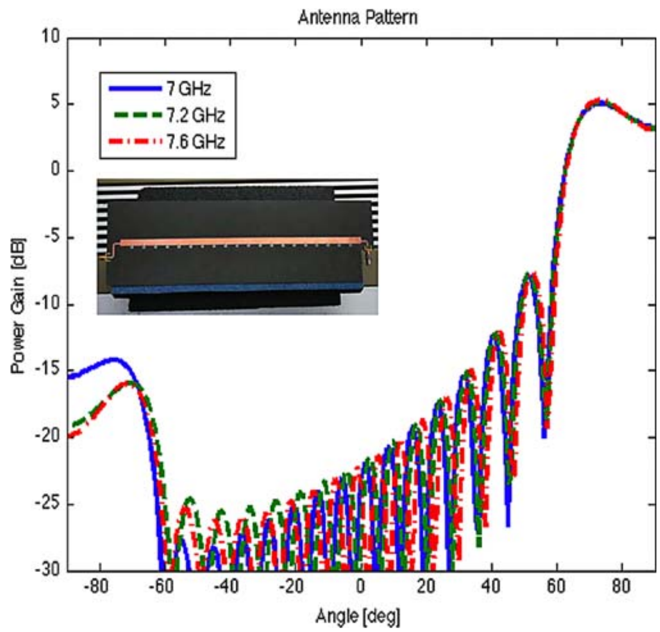

FIGURE 1.

COLLABORATORS

S. Schneider and M. Corwin, AFRL/RY; R. Penno, University of Dayton.

CURRENT SPONSORS

US Air Force Research Laboratory

RECENT PUBLICATIONS

M. Archbold, E.J. Rothwell, L.C. Kempel, and S.W. Schneider, "Beam steering of a half-width microstrip leaky-wave antenna using edge loading," *IEEE Antennas Wireless Prop. Lttrs*, 9, pp. 203–206, 2010.

H. Jiang, R. Penno, K.M. Pasala, L. Kempel, and S. Schneider, "Broadband microstrip leaky wave antenna with inhomogeneous materials," *IEEE Trans. Antennas Propagat.*, 57, pp. 1557–1561, May 2009.

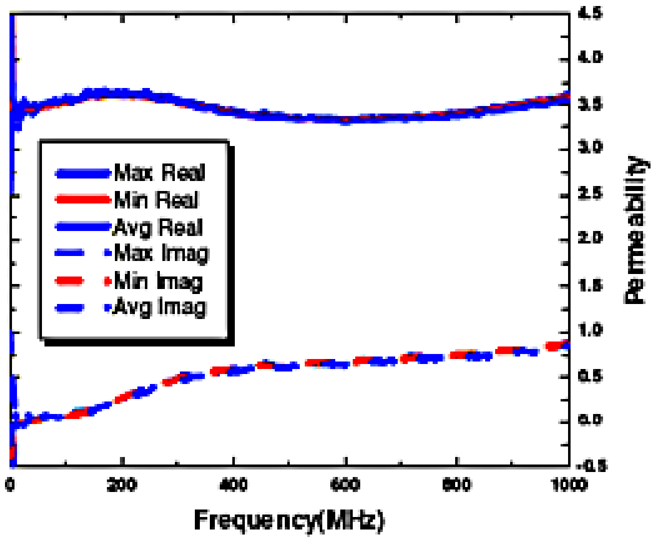

FIGURE 2.

Magneto-dielectric Material Design

Traditional non-conductive materials for use in VHF-K-band and beyond are usually non-magnetic. Such dielectric materials have a variety of uses and have been the subject of concerted design effort for over five decades. Design and synthesis of magneto-dielectric materials (e.g., having a non-trivial relative permeability as well as non-trivial relative permittivity) have undergone a renaissance as of late due to the introduction of advanced material synthesis methods and the more prolific talent in nanocomposite material design. The goal of this research is relatively low-loss materials for use UHF-L-bands having a permeability that is modest (e.g., 2–10 relative units) with comparable relative permittivity. Such materials open the design space for microwave devices such as antennas, radomes, and transmission lines.

The materials have a polymer matrix with metallic and metal oxide inclusions. These inclusions are usually spheroidal, linear (e.g., rods) or platelets. Such inclusions couple individual inclusion impact to realize the desired macroscopic effect. Partners at sister-institutions synthesize the materials developed under this project. Michigan State University provides recommendations on the design (e.g., target permittivity, permeability, loss factors, etc.), characterizes the synthesized coupons, and provides potential application designs (e.g., antennas).

Over the past decade, the upper limit of low-loss materials from this program has advanced from VHF (30–300 MHz) to UHF (300–1000 MHz). New materials that have the potential for use in L- and S-bands have begun to emerge. These materials offer the potential for smaller apertures with wider bandwidth than is typically available. Current research is focused on the most challenging design aspects of resonant structures (e.g., designs that require lower loss factors).

COLLABORATORS

P. Kofinas, Univ. of Maryland; J. Tour, Rice University; J. Xiao, Univ. of Delaware; M. Alexander, AFRL/RX.

CURRENT SPONSORS

Air Force Research Laboratory; Air Force Office of Scientific Research.

RECENT PUBLICATIONS

A. Dimiev, W. Lu, K. Zeller, B. Crowgey, L.C. Kempel, and J.M. Tour, "Low-loss, high-permittivity composites made from graphene nanoribbons," *ACS Appl. Mater. Interfaces*, doi: 10.1021/am201071h, 2011.

T.I Yang, R.N.C. Brown, L.C. Kempel, and P. Kofinas, "Controlled synthesis of core-shell iron-silica nanoparticles and their magneto-dielectric properties in polymer composites," *Nanotechnology*, 22, doi:10.1088/0957-4484/22/10/105601, 2011.

T-I Yang, R.N.C. Brown, L.C. Kempel, and P. Kofinas, "Surfactant-modified nickel zinc iron oxide/polymer nanocomposite for radio frequency applications," *J. Nanopart. Res.*, DOI 10.1007/s11051-010-9887-4, April 2010.

Microtechnology Laboratory

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The Microtechnology laboratory focuses on the development of advanced inorganic and organic micro- and nano- systems for applications in fundamental scientific research, chemical sensing and detecting, biomedical diagnostics and therapy. We are interested in all aspects of micro- and nano- sciences and technologies, including polymer material properties, micro- and nano- processing, sensing and actuation mechanisms, integration and packaging, and other relevant fields. Our current research activities fall into two categories: (1) polymer-based biomedical microelectromechanical systems (BioMEMS) and (2) graphene-based nanosensor and nanoelectronics.

Polymer-based BioMEMS

FACULTY COLLABORATORS: *Arthur Weber, Andrew Mason, Selin Aviyente*

The lab has been working with polymeric materials (such as parylene, PDMS, and SU-8) to fabricate biocompatible and flexible devices for advancing biological research and biomedical implants. Successfully developed devices include an optogenetics-based neural interface and an intraocular pressure sensor. Specifically, we have invented a unique Opto-ECoG (electrocorticographic) neural interface that consists of 32 light emitting diodes (LED) and transparent electrodes on a flexible parylene substrate for epidural optical stimulation and simultaneous recording of cortical neural activities. The ultimate goal of this project is to realize the next generation of brain-machine interfaces based on an emerging optogenetics technology. We have also developed a wireless passive pressure sensor based on an origami design for real-time, continuous monitoring intraocular pressure in glaucoma eyes (Fig. 2). Current studies include *ex vivo* characterization of device performance and improvement of device design. The other focus of our research aims at developing new polymer processing and packaging techniques to enable the long-term biocompatibility and stability of implantable devices and systems.

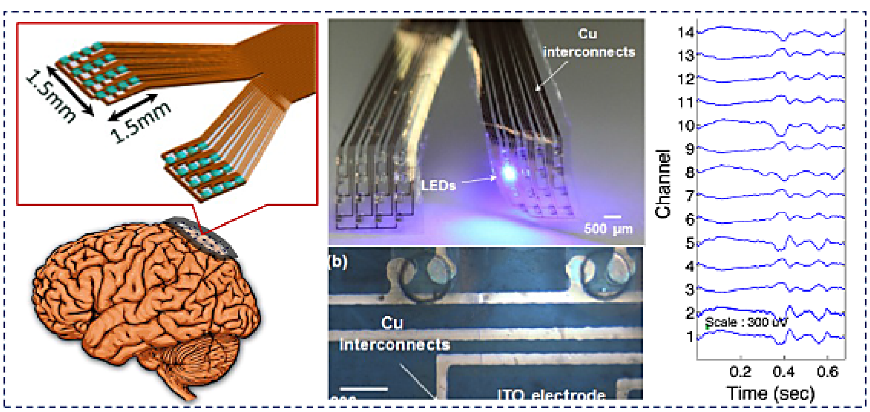

FIGURE 1. An optogenetics-based neural interface has been developed by integrating micro LEDs and transparent electrodes on a single polymer platform. Multichannel, bidirectional interaction with cortical neurons can be achieved through simultaneously optical stimulation and electrical ECoG recording.

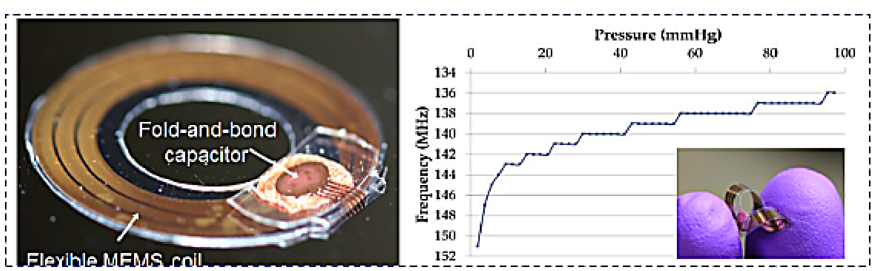

FIGURE 2. A wireless, flexible, passive pressure sensor that is suitable for intraocular pressure monitoring. A pressure sensitivity of 156 kHz/mmHg and a maximum detectable range of 28 mm have been achieved in water.

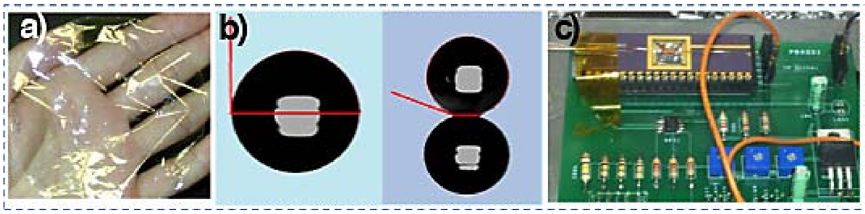

FIGURE 3. Material and packaging related projects: (A) parylene thin film; (B) super hydrophobic parylene substrate; (C) microfluidic package for micro gas chromatography.

Graphene-based Nanosensor and Nanoelectronics

FACULTY COLLABORATOR: *Lixin Dong*

Graphene is a single free-standing atomic layer of carbon and has extraordinary electrical, optical, and thermal properties. Specifically, a few-layer graphene (FLG) structure has a sub-nanometer inter-sheet spacing between stacked graphene sheets, which enables new transduction possibilities for sensing molecular adsorption/desorption, mechanical force/displacement, and physical deformation. Currently, we are developing graphene nanosensors by taking the advantages of inter-layer tunneling and doping effects of FLGs (Fig. 4). Applications of such inter-layered graphene sensors in chemical molecule detection have been demonstrated, showing that the inter-layer configuration can achieve higher sensitivities compared to the most commonly used intra-layer configuration. Our goal is to integrate this inter-layered graphene sensor with a microfluidic platform to realize an automatic and high resolution sensing system for biomolecular detection.

ACKNOWLEDGEMENT

The Microtechnology lab was financially supported in part by Michigan State University, the National Science Foundation (ECCS-1055269), and the U.S. Department of Homeland Security (06-G-024).

SELECTED RECENT PUBLICATIONS

K.Y. Kwon and W. Li, "Integrated Multi-LED Array with Three-dimensional Polymer Waveguide for Optogenetics," *IEEE MEMS 2013 Conference*, Taipei Taiwan, Jan. 21–24, 2013.

Ki Yong Kwon, Brenton Sirowatka, Arthur Weber, and Wen Li, "Opto-µECoG Array: Transparent µECoG Electrode Array and Integrated LEDs for Optogenetics," *IEEE BioCAS 2012*, Hsinchu, Taiwan, Nov. 28–30, 2012.

Nathan Ward, Xiaoyi Mu, Gustavo Serrano, Elizabeth Covington, Çagliyan Kurdak, Edward T. Zellers, Andrew J. Mason, and Wen Li, "Microfluidic-Packaged CMOS Chemiresistor Detector for Micro-Scale Gas Chromatograph," *Micro & Nano Letters*, vol. 7, No. 4, August 2012, pp. 721–724.

Fubo Rao, Haider Almumen, Zheng Fan, Wen Li, and Lixin Dong, "Inter-layer Effects Inspired Graphene Sensors: Design, Fabrication, and Characterization," *Nanotechnology*, 2012, 23, 105501

Xiaopeng Bi, Nathan Ward, Brian Crum, and Wen Li, "Plasma-treated Switchable Wettability of Parylene-C Surface," Proc. of the IEEE-NEMS 2012 Conference, Kyoto, JAPAN, March 5–8, 2012.

GROUP MEMBERS

GRADUATE STUDENTS*:* Haider Al-Mumen, Xiaopeng Bi, Brian Crum, Bin Fan, Ki Yong Kwon, Diana Ramos. UNDERGRADUATE STUDENT: Brenton Sirowatka

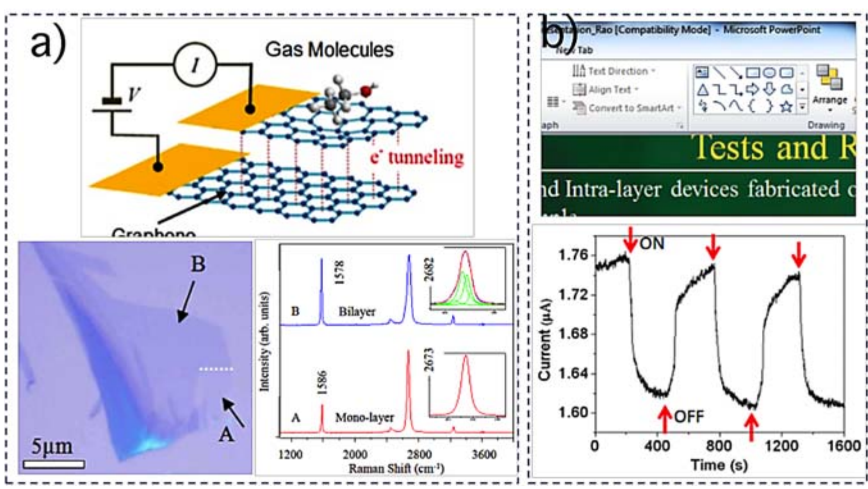

FIGURE 4. (A) An inter-layer sensor has been developed, which uses the inter-layer tunneling effect between stacked graphene sheets. Monolayer or bilayer graphene can be identified through optical microscopy and Raman spectroscopy. (B) A fabrication bi-layered graphene sensor for chemical detection. The graphene resistance decreases upon exposure to 5% ethanol vapor.

Materials & Devices for Electronic & Optical Applications

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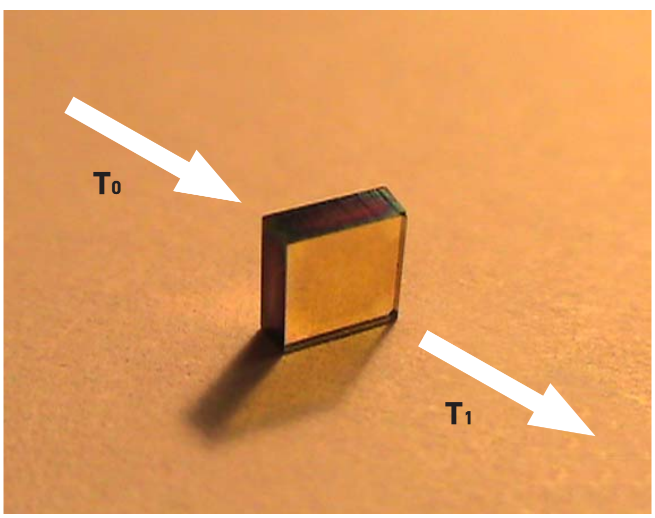
My research area is primarily that of materials and devices for electronic and optical applications. For several years, the principal focus has been on diamond synthesis, characterization, and application. It has been my privilege to collaborate in this endeavor with colleagues from Michigan State University and from the Fraunhofer Center for Coatings and Laser Application.

Antireflection layers for diamond

Single crystalline diamond are of interest for high-power optical applications for a variety of reasons including transparency, high thermal conductivity, and very low birefringence values. Potential applications include intra-cavity diamond components for thermal management in high power lasers in which case optical antireflection coatings are of interest. Figure 1 shows a single crystal diamond with a antireflection layer engineered for maximum transmission at an infrared wavelength of 1.6 micrometers.

Phosphorus n-type doping of diamond

Diamond is of potential interest for semiconductor devices intended for high temperature and or high voltage applications. However this requires doping with intentionally added impurities to achieve n-type and p-type conduction. Although p-type diamond doped by boron impurities is found (albeit rarely) in nature and has been achieved in several laboratories, phosphorus doping



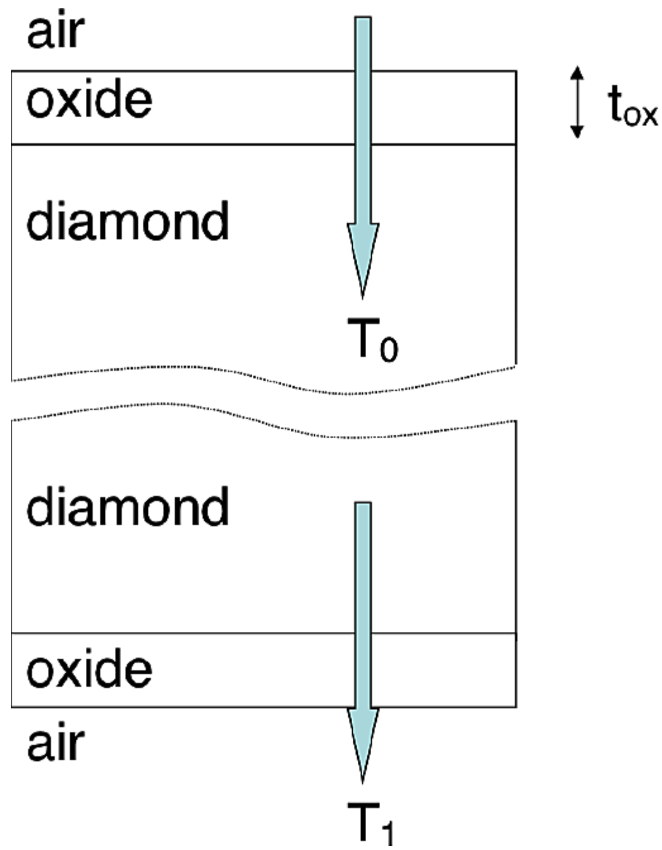


FIGURE 1. Antireflection coated diamond. The coating thickness was designed for maximum transmission at an infrared wavelength of 1.6 micrometers, of interest for certain atmospheric window transmission applications. PECVD depositions of SiO_2, 280 nm thick, were performed on the front and back of single-crystal diamond samples with N_2O and SiH_4 feed gasses at 1 torr pressure and 300°C substrate temperature. Transmission through the coated diamond sample was measured at wavelength increments of 1 nm, resulting a center wavelength transmission of 98.7% with a standard deviation of 0.4%, as compared to the modeling result of 99.2%.

for n-type diamond is more problematic and success has only been reported by a handful of groups. Simply adding an element with an extra electron does not ensure n-type dopoing. Nearest neighbor separation between carbon atoms in the diamond crystal is so small that impurities can cause local bond distortion that causes the donor energy level to be deep in the gap. Work by doctoral student Matthais Muehle is currently investigating growth of phosphorus doped single crystal diamond as n-type material.

DOCTORAL STUDENT

Matthias Muehle

RECENT PUBLICATIONS

D.K. Reinhard, D.T. Tran, T. Schuelke, M.F. Becker, T.A. Grotjohn, J. Asmussen, "SiO2 antireflection layers for single-crystal diamond," *Diamond and Related Materials*, 25, 84, (2012).

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Electromagnetics Group: Materials Characterization

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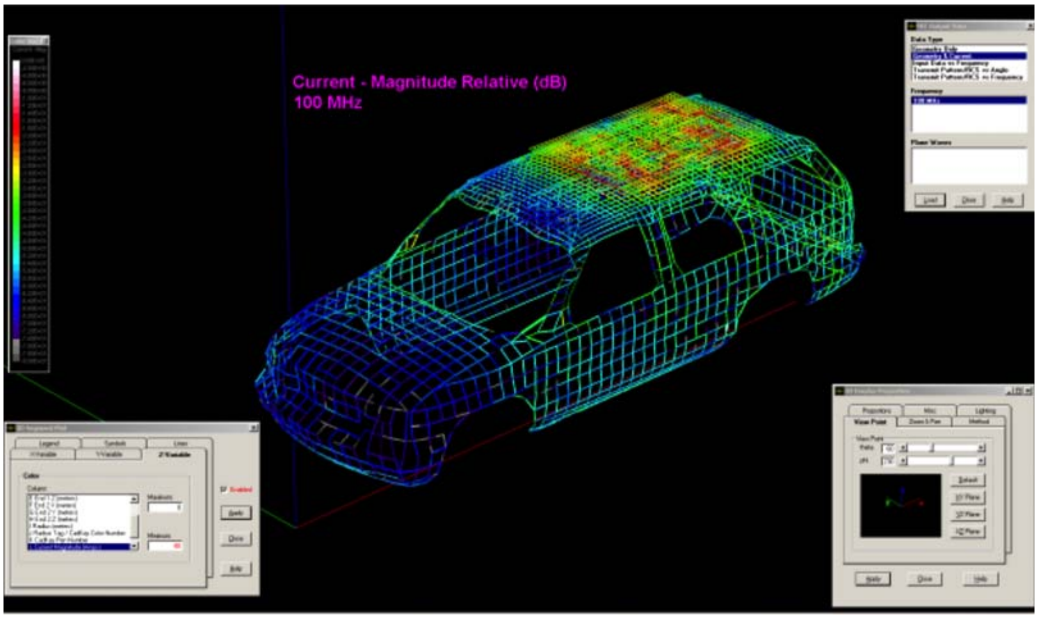

The electromagnetic research group consists of four faculty members (Rothwell, Kempel, Balasubramaniam, and Chahal), and carries out a wide variety of research projects spanning the computational, theoretical, and experimental domains. The group comprises approximately 25 graduate and undergraduate students, post docs, and visiting scholars. This document describes work led by Professor Rothwell. Note that all group members collaborate widely, and most projects overlap among the domains.

Self-structuring antennas

Self-structuring antenna systems are a new and innovative type of antenna that consists of a switchable template coupled to a controller and a feedback sensor that allows the system to change its electrical shape in response to changes in frequency, operating mission, or physical environment, and to self-repair in response to being damaged. Prof. Rothwell is the inventor on the fundamental patent held by MSU, and two additional patents are pending. The spin-off company Monarch Antennas, Inc. (*www.monarchantenna.com*) was created as a joint venture between Delphi Technologies and MSU to commercialize the technology. Applications include antennas for ground and air vehicles, cellular telephones, tablet computers, and televisions.

SPONSORS

PAST: Delphi Research, MEDC, NASA. CURRENT: U.S. Navy, U.S. Air Force.

RECENT PUBLICATIONS

R. O. Ouedraogo, E. J. Rothwell and B. J. Greetis, “A Reconfigurable Microstrip Leaky-wave Antenna with a Broadly Steerable Beam,” *IEEE Trans. Antennas Propagat.*, 59, 3080–3083, 2011.

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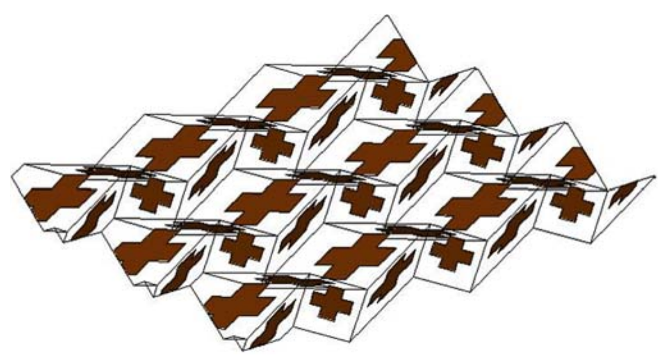
C.M. Coleman, E.J. Rothwell, J.E. Ross, and L.L. Nagy, “Self-Structuring Antennas,” *IEEE Antennas Propagat. Mag.*, 44, 11–22, 2002.



Miniaturized antennas and meta-material systems

Metamaterials are artificially constructed materials that have properties not found in nature, specifically negative permittivity and permeability. These properties may be exploited in a number of clever ways to create miniaturized antennas and microwave systems. We have explored techniques for optimizing the structure of metamaterials and have created several new types of miniaturized antennas, microwave filters, and frequency-selective surfaces. We have also explored novel techniques for tuning metamaterials including the use of origami folding of planar structures.

COLLABORATORS

Shih-Yuan Chen, National Taiwan University; Alejandro Diaz, Leo Kempel, Prem Chahal, MSU

SPONSORS

PAST: NSF. CURRENT: Air Force Research Laboratory.

RECENT PUBLICATIONS

R. Ouedraogo, E. Rothwell, A. Diaz, and K. Fuchi, "Waveguide Bandstop Filter Design Using Optimized Pixelated Inserts," *Microwave and Opt. Tech. Lett.*, 5, 141–143, 2013.

K. Fuchi, J. Tang, B. Crowgey, A.R. Diaz, E.J. Rothwell, and R.O. Ouedraogo, "Origami Tunable Frequency Selective Surfaces," *IEEE Antennas and Wireless Propagat. Lett.*, 11, 473–475, 2012.

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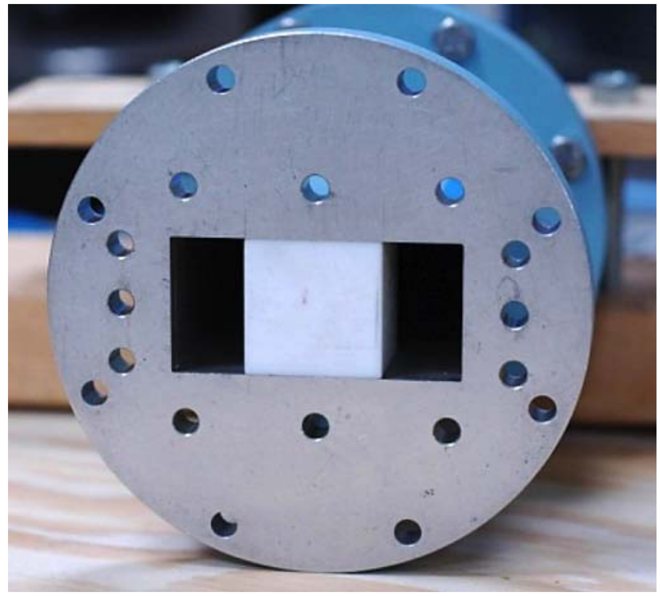
R. Ouedraogo, E. Rothwell, A. Diaz, K. Fuchi, and A. Temme, "Miniaturization of Patch Antennas Using a Metamaterial-Inspired Technique," *IEEE Trans. Antennas and Propagat.*, **60**, 2175–2182, 2012.

Characterization of the electromagnetic properties of materials

The EM research group has been developing techniques for characterizing the electromagnetic properties of materials for nearly 25 years. Recently the group has been examining methods to characterize absorbing materials, composite materials, artificially engineered materials, and anisotropic materials, and has been working with researchers at several universities to develop applications for these materials. We have developed specialized applicators to be used with free space (antenna-based), waveguide, microstrip, and stripline systems.

COLLABORATORS

Michael Havrilla, Milo Hyde, Air Force Institute of Technology; Lydell Frasch, Boeing; Andrew Bogle, University of Dayton; Leo Kempel, Balasubramaiam Shanker, Lawrence Drzal, Martin Hawley, MSU.



SPONSORS

PAST: Dow Chemical, Motorola, Boeing. CURRENT: Air Force Office of Scientific Research, Air Force Research Laboratory, General Electric.

RECENT PUBLICATIONS

R. A. Fenner, E. J. Rothwell, and L. L. Frasch, "A comprehensive analysis of free-space and guided-wave techniques for extracting the permeability and permittivity of materials using reflection-only measurements," *Radio Science*, 47, RS1004, pp. 1004–1016, January 2012.

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M. W. Hyde IV, M. J. Havrilla, A. E. Bogle, E. J. Rothwell, G. D. Dester, "An Improved Two-Layer Method for Nondestructively Characterizing Magnetic Sheet Materials Using a Single Rectangular Waveguide Probe," *Electromagnetics*, 32, 411–425, 2012.

Applied Materials Group

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The Applied Materials Group (AMG) is focused on the integration of novel smart materials into micrometer-sized devices. Our main emphasis has been on vanadium dioxide (VO_2) thin films. VO_2 exhibits a solid-solid phase change, which can be thermally induced at a temperature of ~ 68°C. During this phase transition, the material goes through an electronic/structural transformation (Mott-Peierls type) during which many of the material properties (e.g., electrical, optical, mechanical) change abruptly. The multifunctional properties of VO_2, the relative proximity of its transition temperature to room temperature, and its intrinsic hysteretic behavior—which gives the material memory capabilities—make this material very attractive for practical applications.

In 2010, our group demonstrated that VO_2-coated micromechanical structures experience very large deflections during the coating's phase transition; deflections much larger than what could be accomplished by solely the thermal expansion difference between the microstructure and the coating. It was found that the mechanism responsible for the observed deflections was associated to the crystallographic changes that the coating experiences during its structural phase change.

Given the repeatability, large strain energy density, robustness, and inherent multifunctionality that VO_2 brings to MEMS actuators, these devices are expected to replace currently used actuation technologies. VO_2 thin films have successfully been integrated on MEMS actuators (see Figure 1). Our VO_2-based micromechanical actuators can oscillate at frequencies around 1 kHz —which is considerably fast for a thermal-based actuation process—while sustaining their large vibration amplitudes. Figure 2 shows the fabrication process for the MEMS actuators.

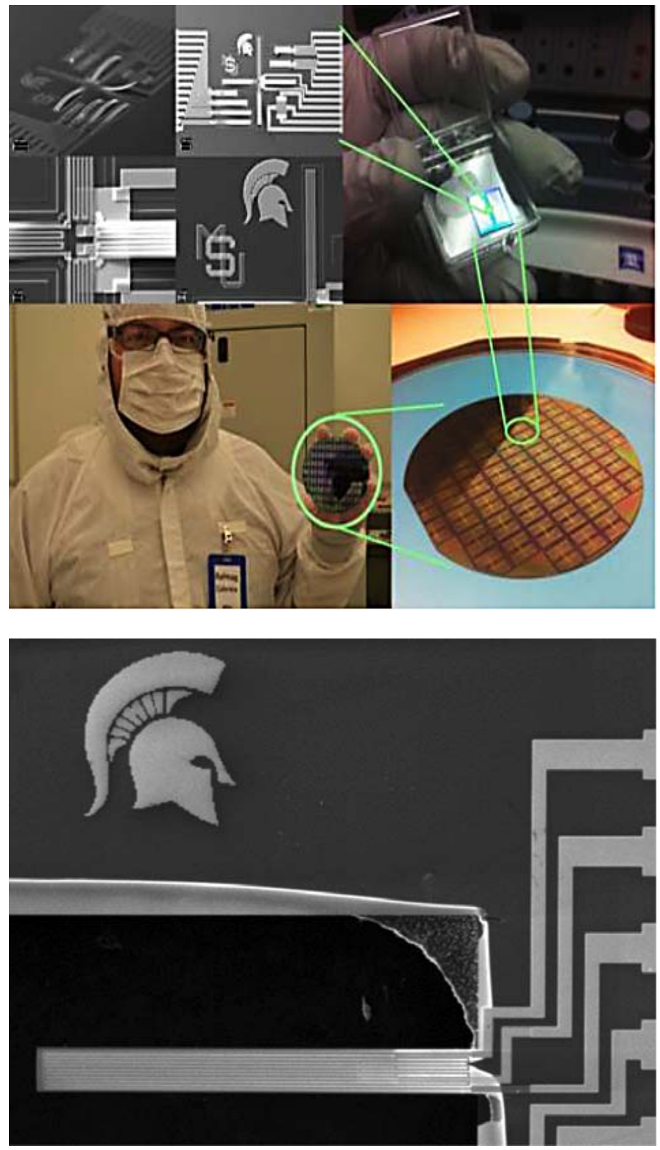

FIGURE 1. *Top:* VO_2-based MEMS actuator chip design. Mr. Rafmag Cabrera (graduate student) holding wafer. *Bottom:* Fully suspended MEMS actuator with patterned resistive heaters.

The abrupt changes in VO_2's optical properties, and its inherently hysteretic behavior has also been used to program and project near infrared (NIR) images. Figure 3 shows a programmed and projected NIR image. The image was programmed by photothermal actuation from scanning a focused red laser (λ = 650 nm) on localized regions of the VO_2 thin film. The scanned regions of the VO_2 thin film experience the phase change, and become much more reflective (less transparent) to NIR than the regions that were not scanned. A NIR projecting laser beam (λ = 1.55 mm) was diffused into a square shape of

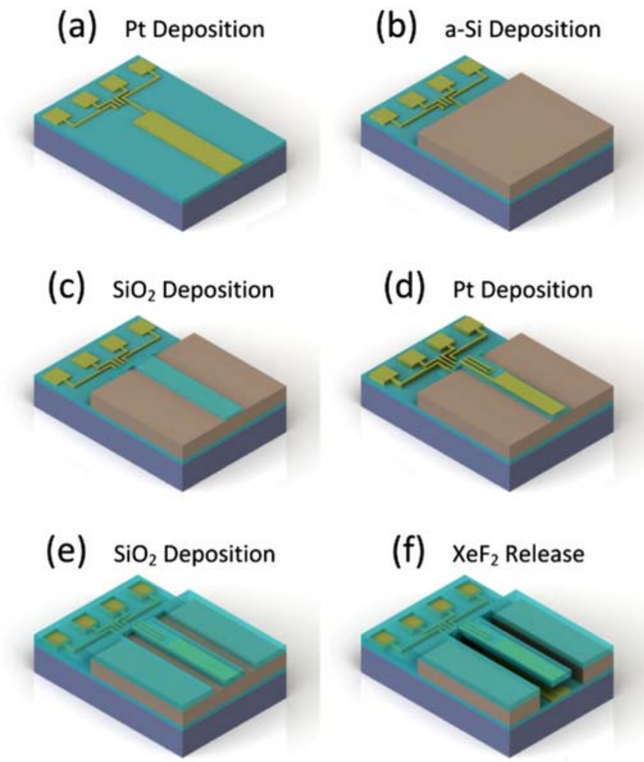

FIGURE 2. General fabrication process flow.

uniform intensity on the entire VO_2 film. The transmitted NIR beam was projected on a laser beam profiler.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant ECCS-1139773 (CAREER Program).

RECENT PUBLICATIONS

[*† denotes a graduate student directly supervised by Nelson Sepúlveda and ‡ denotes an undergraduate student directly supervised by Nelson Sepúlveda.*]

N. Dávila†, R. Cabrera†, and N. Sepúlveda, "Programming and projection of near IR Images using VO_2 films," *IEEE Photonics Technology Letters*, 24, 20, pp. 1830–1833 (2012).

E. Merced†, N. Dávila†, D. Torres‡, R. Cabrera†, F. E. Fernández, and N. Sepúlveda, "Photothermal actuation of VO_2:Cr-coated micro-cantilevers in air and aqueous media," *Smart Mater. and Struct.*, 21, 105009, (2012).

A. Rúa, R. Cabrera†, H. Coy, E. Merced†, N. Sepúlveda, and F.E. Fernández, "Phase transition behavior in microcantilevers coated with M1-phase VO_2 and M2-phase VO_2:Cr thin films," *Journal of Applied Physics*, 111, 104502, (2012).

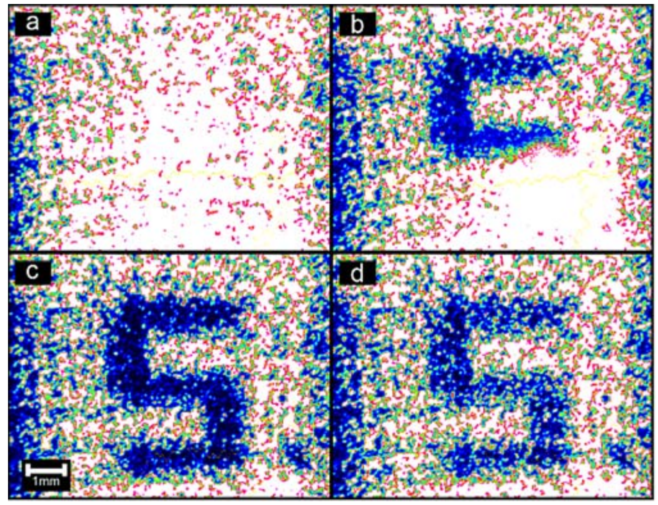

FIGURE 3. Programmed and projected NIR image: (A) at 55°C before laser scanning, (B) during writing laser scanning, (C) right after the writing laser scan finished, and (D) programmed images 5 minutes afte scanning.

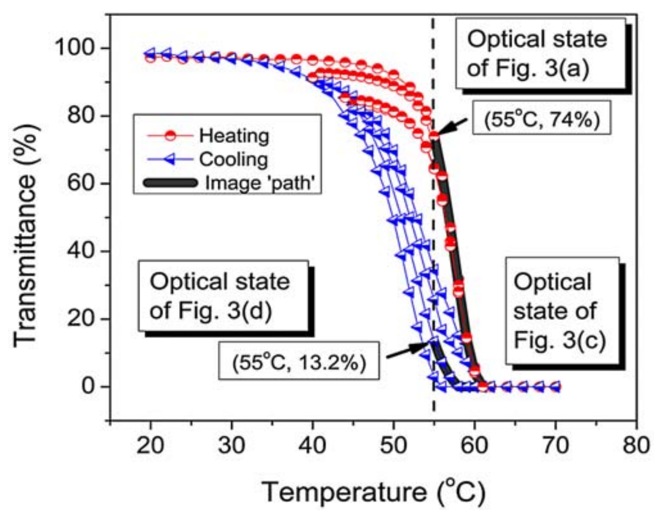

FIGURE 4. NIR transmittance through VO_2 during heating and cooling temperature cycles. The different optical states shown in Figure 3 are identified.

E. Merced†, R. Cabrera†, N. Dávila†, F.E. Fernández, N. Sepúlveda, "A micro-mechanical resonator with programmable frequency capability," *Smart Mater. Struct.*, 21, 035007 (2012).

GROUP MEMBERS

PHD STUDENTS: Rafmag Cabrera, Emmanuelle Merced, Noraica Dávila, David Torres, Kidany Acevedo. UNDERGRADUATE STUDENTS: Caitlin Ramsey, Ariel Rose.

Plasma Theory and Simulation Group

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The Plasma Theory and Simulation Group engages in theoretical and computational plasma physics research, including algorithm, model, and code development, with a broad range of applications.

The PTSG code suite is distributed for free on the internet, including full source code, and has provided the basis for models incorporated in codes around the world. The code suite has been used by more than 1000 researchers worldwide, and played a key role in over 350 research publications in the past decade. The PTSG moved from the University of California at Berkeley to Michigan State University in 2011.

PTSG pioneered models for bounded plasmas, including self-consistent circuit boundary conditions. It also pioneered models for collisional plasmas, including multiple background gases and multi-species chemistry. PTSG also pioneered the development of object-oriented models for plasma codes, extending lifetime and enabling dynamic model exchange.

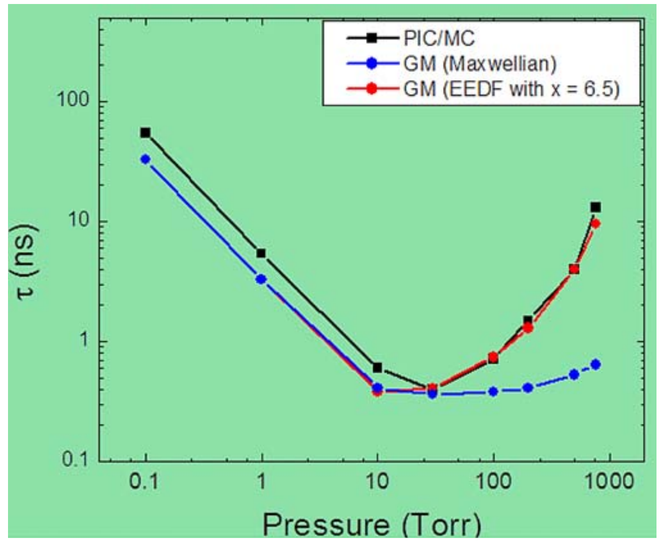

FIGURE 1. Kinetic global model comparison with fully kinetic PIC and classical global model.

Kinetic Global Model

PTSG devised a new model for the rapid modeling of large numbers of species and reactions in high pressure plasmas, called the kinetic global model. This is a spatially independent model in which the reaction rates are determined by convolution of energy dependent cross sections with a parameterized distribution function.

High Performance Computing (HPC)

Models for massively parallel systems, including multi-core/multi-CPU clusters, GPU clusters, and specialized supercomputers with advanced programmable cache and memory topology capabilities. An example of HPC research is the study of partial sorting on the null collision model on GPU systems, where the use of bandwidth within GPU processors is crucial in performance.

High Voltage Multipactor and Breakdown

These study range from high vacuum multipactor in superconducting RF (SRF) cavities, to high power microwave breakdown in air. In the resonant multipactor process, electron impact in the range ~100 eV to a few keV can result in ejection of more than one secondary electron per impact, so that trajectories that result in resonant impacts in this range can lead to a rapidly growing electron current, and ultimately surface heating, damage, and desorption of atoms which can become ionized and do damage (Fig. 2). A similar sequence occurs with background gases, but quickly transitions into a plasma discharge and potentially an arc. These breakdown effects are often the limiting factor in high voltage devices ranging from accelerators to microwave sources for radar, as well as insulators on power transmission lines, high voltage pulsed systems, and many more.

Plasma-Assisted Combustion

PTSG is developing techniques for influence the electron energy distribution function by preferentially heating one part of the distribution, leading to a bias for one set of reactions

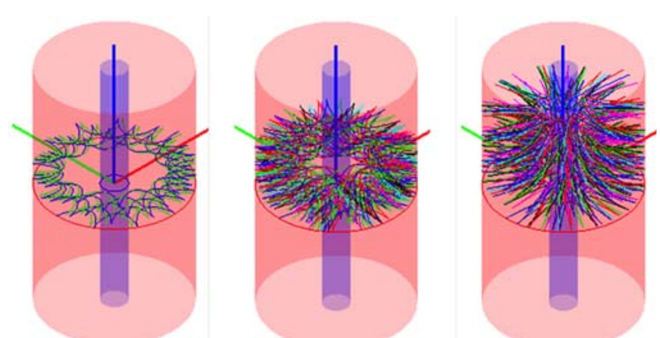

FIGURE 2. Multipactor discharge growth in a superconducting RF cavity.

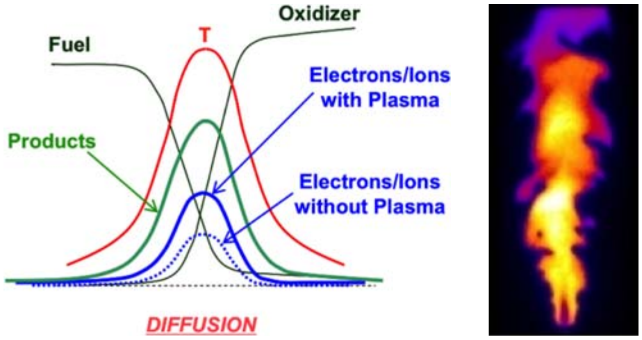

FIGURE 3. Reactant balances and plasma-assisted combustion flame.

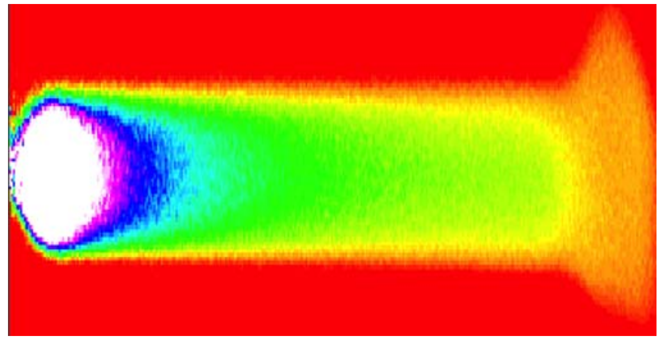

FIGURE 4. Electron density in a capacitively compled RF discharge.

over another (Fig. 3). This can be used to select reaction chains for more efficient fuel cracking and combustion, as well as selecting chains which lead to lower pollutant production. Current efforts focus on the relatively simple atomic reactions of methane, and after demonstration of the technique, will move on to more complex fuels including gasoline, diesel, and biofuels. Biofuels, in particular, can be difficult to combust effectively in standard conditions, but plasmas have proven an effective way to improve the process.

Low-Temperature Plasmas

PTSG models a broad range of low temperate plasmas, with electrons temperatures of a few eV. These include materials processing plasmas (Fig. 4), lighting plasmas, plasma thrusters, and many more. In these plasmas the main focus is on the generation and profile of the plasmas, as well as the control of the fluxes to surfaces, the generation of excited states and consequent photon emission, or the efficient generation of charged particles for acceleration in a thruster.

Microdischarges and Dielectric Barrier Discharges

A variant of low-temperature plasmas includes high pressure non-equilibrium discharges. This family of discharges includes atmospheric pressure non-equilibrium microdischarges, as well as dielectric barrier discharges (Fig. 5). These discharges are often ~100 microns in spatial extent, but have very high peak densities, and are characterized by sharp density and effective temperature gradients that have non-local properties due to intense driving fields localized to sheath regions.

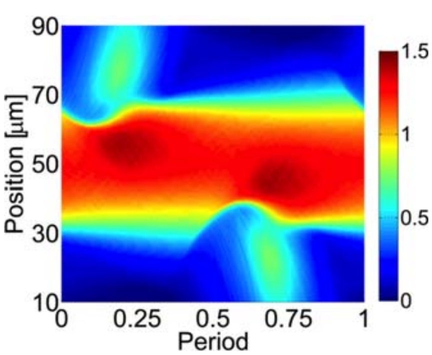

FIGURE 5. Spatio-temporal ion density in a dielectric barrier discharge driven at 13.56 MHz.

Basic Space Charge Physics

PTSG also studies basic physics such as space charge physics, interaction of waves with plasmas, plasma heating and transport. For example, microscopic features under high field stress can eject electrons via a tunneling process called field emission. However, the current emitted from such a tip rapidly shields the field at the surface, limiting the emitted current to below the classical space charge limit (Fig. 6).

Strongly Coupled Plasmas

Strongly coupled plasmas, including ultra-cold plasmas, are an interesting new class of plasmas in which the potential energy of the system exceeds the kinetic energy. These plasmas exhibit properties similar to liquids and solids. Interesting applications of this class of plasmas include formation of dynamic micro-structures, such as rapidly directed antennas, multi-directional optical switches.

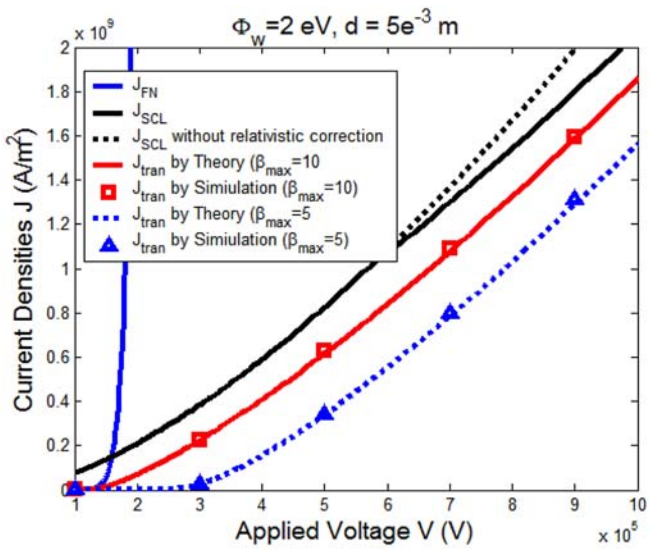

FIGURE 6. Transition from field emission to space-charge-limited field emission for a sharp feature.

Nanomaterials and Nanoelectronics Group

Chuan Wang | ***www.msu.edu/~cwang*** | ***https://sites.google.com/site/cwangnano/***

The Nanomaterials and Nanoelectronics Group led by Prof. Wang is an interdisciplinary research program which links electrical engineering, materials science, physics, chemistry, and some process development. The research in Wang's group encompasses various aspects of nanoscience and nanotechnology, from novel nanomaterial synthesis and assembly to applications toward system-level nanoelectronics and macroelectronics. The aim is to develop technology platforms that can fully utilize the advantages of different nanomaterials toward scalable, practical, and high-performance electronic systems.

The research in Wang's group has led to 33 journal publications, most of which are published in high impact journals including *Nature Materials, Nature Communications, Chemical Society Reviews, Nano Letters, ACS Nano, and Advanced Materials*. The research has also been reported by *Nature, Science, Technology Review, Time, abc News, CNET, Discovery News, EE Times, nanotechweb.org, phys.org, ScienceDaily*, and many more.

The ongoing research in Prof. Wang's research group includes the following three main directions:

Semiconducting carbon nanotube thin-film for system-level flexible electronics

Single-wall carbon nanotubes possess superior electrical properties and offer new entries into a wide range of novel electronic applications that are unattainable with conventional Si-based devices. The field initially focused on the use of individual nanotube as the channel material for ultra-scaled nanoelectronic devices. Despite the tremendous progress made with individual nanotube transistors and circuits, the challenges in the deterministic assembly of nanotubes with nm-scale accuracy and the coexistence of metallic and semiconducting nanotubes have proven to be major technological barriers. In order to overcome the challenging task of integrating nanotube devices for scalable and practical electronic systems, Wang's group has developed a platform for solution-based processing of semiconductor-enriched carbon nanotube networks that has led to low-cost wafer-scale fabrication of thin-film transistors (TFTs) with excellent yield and highly uniform performance on mechanically flexible substrates. Such transistors exhibit on-current, transconductance, and field-effect mobility up to 15 μA/μm, 4 μS/μm, and 100 cm^2/Vs, respectively, which are respectable performances for a room temperature solution-based process. Based on the semiconducting carbon nanotube TFTs, a wide range of macro-scale system-level electronics have been demonstrated, including flexible integrated circuits, active-matrix organic light-emitting diode (AMOLED) displays, and a smart interactive electronic skin (e-skin) that can simultaneously map and respond to pressure stimulus. With emphasis on large-area systems where nm-scale accuracy in the assembly of nanotubes is not required, the work presents a unique niche for nanotube electronics by overcoming their limitations and taking full advantage of their superior electrical and physical properties. The work shows carbon nanotubes' immense promise as a low-cost and scalable TFT technology for flexible electronic systems with excellent performance.

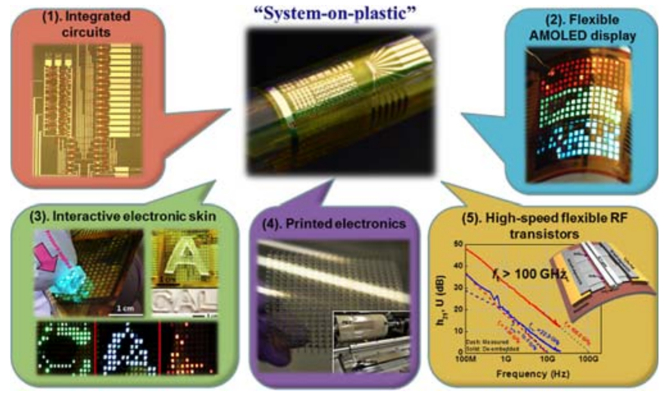

FIGURE 1. Different types of electronic components built on mechanically flexible substrates for "system-on-plastic" applications.

As a demonstration of a meaningful and practical system-level flexible electronics, an interactive electronic -stem-level multifunctional and interactive electronic-skinskin was demonstrated recently in Wang's group and the result was published in *Nature Materials*. Different electronic components, including integrated circuits for signal processing, various types of sensor networks (pressure, temperature, and light) for ambient environment detection, and OLED displays for interactive response, are monolithically integrated on one single piece of flexible substrate. This work represents a new class of flexible macroelectronics that can conformally cover any surface and detect, spatially map, and respond to various types of stimuli, which could find wide range of applications

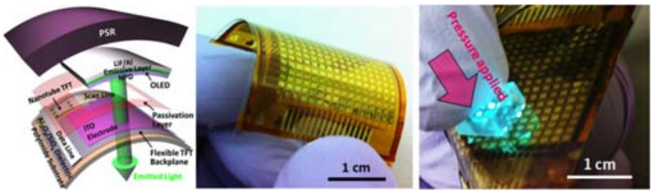

FIGURE 2. Electronic skin system capable of spatially mapping the applied pressure and providing instantaneous feedback by emitting light through the monolithically integrated AMOLED display.

in novel input and control devices, robotics, and biomedical applications such as prosthesis and health monitoring.

Nanomaterial-based radio-frequency electronics

Many nanomaterials offer excellent carrier mobility and are thus suitable for ultrahigh-speed transistors and integrated circuits. Wang's group has been actively exploring using carbon nanotubes, graphene, 2-dimensional III-V (InAs) nanomembranes, and 2-dimensional layered semiconductors (MoS_2) for radio-frequency electronics. An innovative self-aligned T-gate device platform, which enabled the fabrication of ultrashort channel RF transistors with minimized parasitic capacitances and superior frequency response was proposed. Recent progress along this direction includes the development of RF transistors that can be operated at extremely high frequency (EHF) regimes on mechanically flexible substrates for the emerging lightweight, flexible electronics. One grand challenge in creating flexible RF transistors is to identify the channel material that can simultaneously offer mechanical flexibility and high performance (i.e., high mobility). To solve this dilemma, Wang's group reported the transfer printing of ultrathin InAs nanomembranes with thicknesses as small as 10 nanometers as the channel semiconductor for flexible transistors. By employing the "self-aligned" fabrication scheme to allow ultrashort channel (~ 75 nm) with minimal parasitic capacitances, coupled with the high mobility of the III-V material, flexible RF transistors with an unprecedented speed of 105 GHz was demonstrated, which represents one of the fastest performances for flexible electronics. This work could lead to vast applications in lightweight, wearable wireless communication devices.

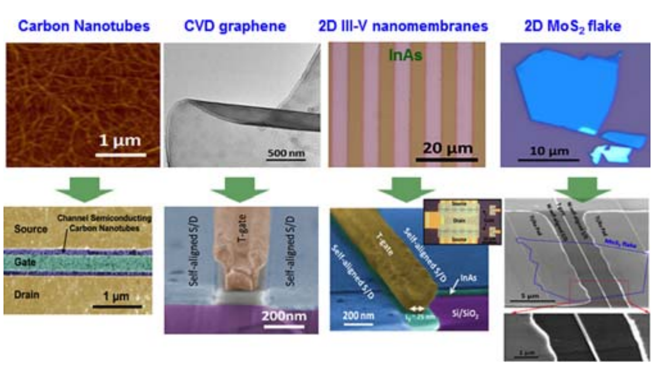

FIGURE 3. Various types of nanomaterials used for RF transistors.

Electronic type- and chirality-controlled synthesis of horizontally aligned carbon nanotubes

Prof. Wang developed wafer-scale chemical vapor deposition (CVD) synthesis and transfer of ultrahigh density (>50 tubes/µm) horizontally aligned carbon nanotubes on quartz substrates, which was proven to be an effective way of gaining control over synthesized nanotube orientation and position, leading to scalable fabrication of high-performance short-channel nanotube transistors and CMOS integrated circuits. The remaining major challenge in the carbon nanotube field is to control the electronic type (metal vs. semiconductor) and chirality of the as-grown nanotubes. Wang's group has recently achieved the chirality-controlled synthesis of single-wall carbon nanotubes with predefined chiralities, which has been an important but elusive goal in the nanotube field for almost two decades. In his recent paper published in *Nature Communications*, a general strategy for producing carbon nanotubes with predefined chiralities is proposed, which uses purified single chirality nanotubes as seeds for subsequent metal-catalyst-free vapor-phase epitaxial growth. This approach is analogous to the epitaxial growth of semiconducting thin-film or simply "cloning of carbon nanotubes." Using this approach, aligned semiconducting nanotubes and metallic nanotubes with predefined chiralities have been successfully synthesized, and the Raman spectroscopy unambiguously confirms that the original chiralities of the nanotube seeds are preserved. The chirality-controlled nanotube synthesis could enable a wide range of fundamental studies, technological developments, and applications in electronics devices and integrated circuits.

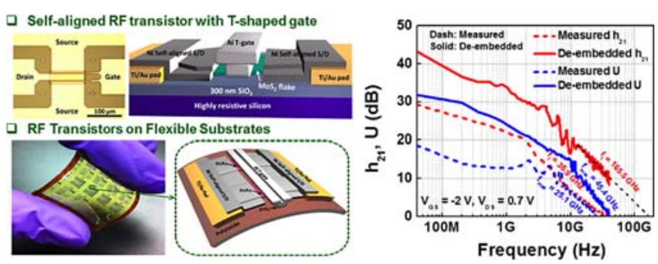

FIGURE 4. Flexible RF transistors with the self-aligned T-gate platform exhibit cutoff frequency above 100 GHz.

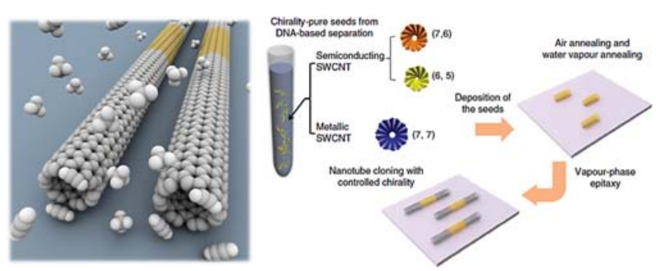

FIGURE 5. Clone the carbon nanotubes: chirality-controlled synthesis of horizontally aligned carbon nanotubes,

Research Centers

BEACON Center for the Study of Evolution in Action

www.beacon-center.org

BEACON is an interdisciplinary and inter-institutional NSF Science and Technology Center directed by Dr. Erik Goodman, Professor of Electrical and Computer Engineering. The BEACON Center for the Study of Evolution in Action was founded with the mission of illuminating and harnessing the power of evolution in action to advance science and technology and benefit society. Research at BEACON focuses on biological evolution, digital evolution, and evolutionary applications in engineering, uniting biologists who study natural evolutionary processes with computer scientists and engineers who are harnessing these processes to solve real-world problems.

Developers of evolutionary algorithms have long borrowed high-level concepts from biology to improve problem-solving methods, but have not always captured the nuances of evolutionary theory. Likewise, studying the evolution of artificial systems can provide biologists with insight into the dynamics of the evolutionary process and the critical factors underlying emergent properties and behaviors. BEACON promotes the transfer of discoveries from biology into computer science and engineering design, while using novel computational methods and systems to address complex biological questions that are difficult or impossible to study with natural organisms.

BEACON is headquartered at Michigan State University, with partners at North Carolina A&T State University, University of Idaho, University of Texas at Austin, and University of Washington.

BEACON research is loosely grouped into three research areas, each addressing a broad theme that cuts across computational and biological thinking at a different level.

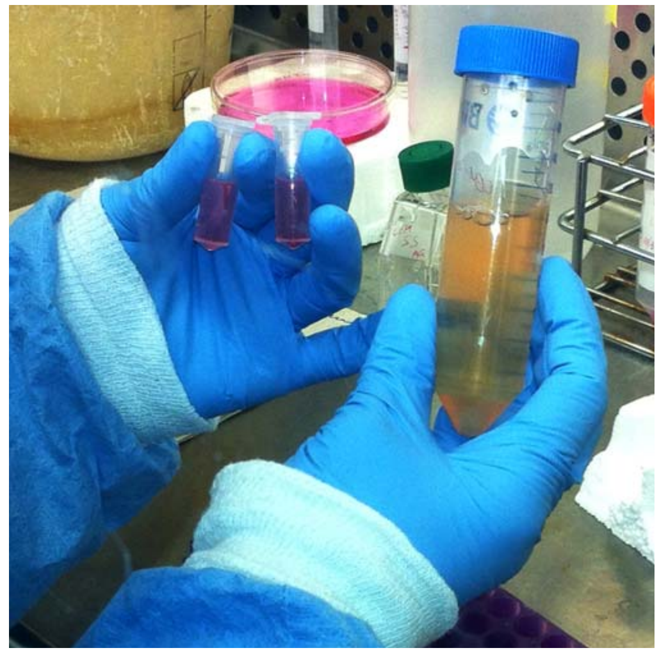

FIGURE 1. Viruses, bacteria, and other microorganisms are the subject of experimental evolution studies.

RESEARCH THRUST 1

Evolution of Genomes, Networks and Evolvability

This thrust seeks to understand the evolution of genome architecture and the processes that govern the production of genetic and phenotypic variation, and how to model these processes to enable better engineering design. Many investigators are studying the actual processes of speciation and adaptation, testing hypotheses about how the process works. Other research themes include: evolution of gene networks underlying complex traits; applying evolutionary perspectives to synthetic biology; and the process and consequences of adaptation to environmental change. BEACON uses a variety of techniques, including experimental evolution in biological and digital organisms, mathematical modeling and simulation, and integrating data from field and lab. Biological insights yield new approaches to engineering design using evolutionary computing.

RESEARCH THRUST 2

Evolution of Behavior and Intelligence

Research in this area focuses on the evolution of behavior of individuals, particularly in the context of social behavior, including cooperation, social coordination,

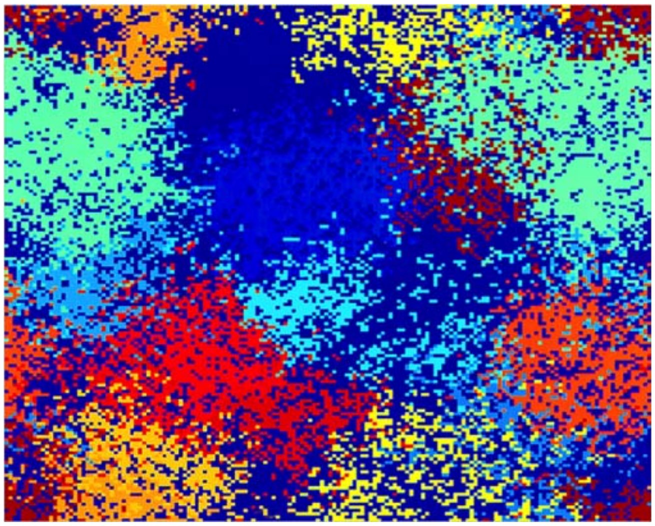

FIGURE 2. A virtual petri dish of digital organisms.

and communication. Researchers are studying behavior in biological organisms such as stickleback fish, birds, and hyenas, but also in digital organisms. Digital evolution has proven to be a powerful tool in which data gathered from biological organisms can be applied to recreate the evolution of complex behavior in digital organisms. By observing the evolution of self-replicating digital organisms, we can understand the conditions that led to the evolution of complex behaviors in biological organisms. Another major theme in this group is using evolutionary computation to create better, smarter electronic and robotic systems, such as dynamic control systems that respond to the environment, improved biometric detection systems for security, character recognition algorithms, and robots that can navigate on their own through environments that may change unpredictably. About a dozen BEACON faculty members do research on evolutionary computation for solution of problems in engineering and computer science.

RESEARCH THRUST 3

Evolution of Communities and Collective Dynamics

Research in this group focuses on the evolution, stability, and emergent properties of assemblages of organisms, considering both their ecological properties and their ability to perform collective tasks. Several projects are focusing on the maintenance of phenotypic variation through collective dynamics. Others are interested in metagenomics, or the study of the collected genomes of all of the microbes in a shared environment. Because the vast majority of these microbes cannot be cultured and studied in a lab in the traditional manner, the ability to directly sequence genomes from, e.g., a soil sample, holds great promise for understanding microbial communities and their interactions with the environment. Finally, some of researchers in this theme are exploring engineering applications inspired by biological studies of collective dynamics.

ACKNOWLEDGMENTS

The BEACON Center is supported by an NSF Science and Technology Center cooperative agreement (DBI-0939454).

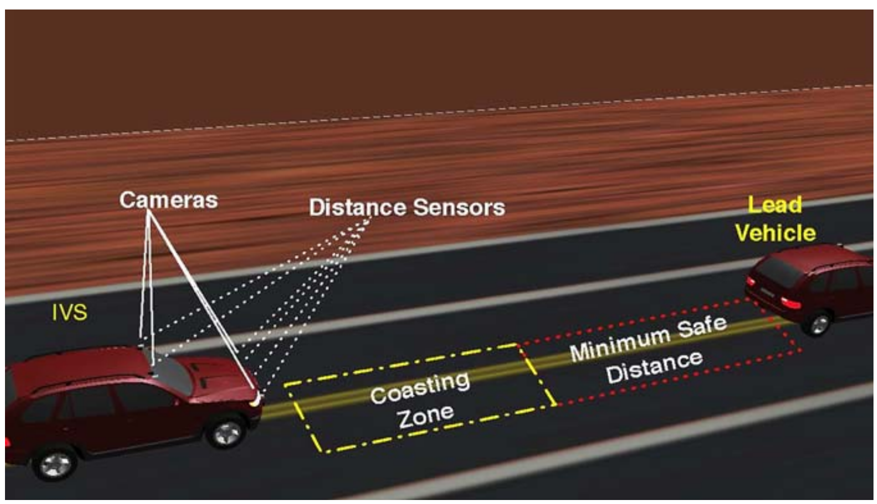

FIGURE 3. Evolutionary algorithms can help make safer cars.

Fraunhofer USA Center for Coatings and Laser Applications

http://www.ccl.fraunhofer.org/

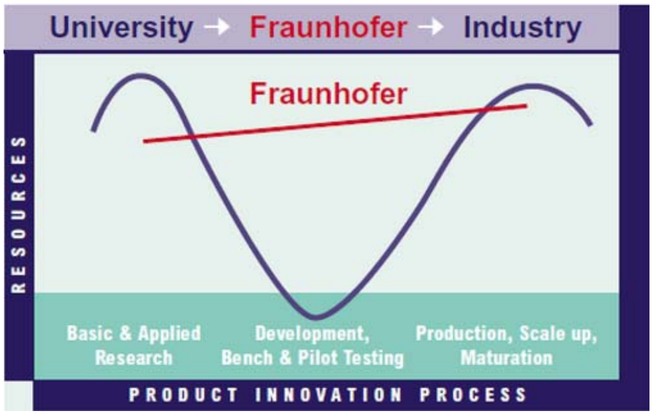

FIGURE 1. Bridging the gap between research and industry.

The Fraunhofer USA Center for Coatings and Laser Applications (CCL), in partnership with Michigan State University (MSU), provides innovative R&D services based on its expertise in coating and laser technology. It is a nonprofit organization providing research services to its customers who include federal and state governments, multinational corporations, and small- to medium-size companies. The overall aim of the entire Fraunhofer organization is to bridge the gap between research and industry by providing top notch applied research services to its customers, helping to enhance their competitive edge!

The Fraunhofer USA Center for Coatings and Laser Applications comprises two divisions. The Laser Applications Division is based in Plymouth, Michigan, and carries out research and prototype applications development in the field of laser materials processing. The division has a wide range of expertise in laser processing technology including advanced laser and hybrid laser welding technology, cutting, cladding and surface treatment. It is continually active in providing state-of-the-art laser technology solutions for a wide range of industrial fields, including automotive, aerospace, ship building, defense, and oil and gas exploration industries.

The Coating Technology Division (based on the MSU campus in East Lansing, Michigan) specializes in plasma-assisted technologies such as PVD (physical vapor deposition), CVD (chemical vapor deposition) diamond coating and synthesis, microwave materials processing, and microwave plasma and machine development. Our experience with ceramic coating technologies advances development in wear resistant and decorative coatings. Our capability in carbon-based materials synthesis and film deposition technologies includes diamond and diamond-like carbon synthesis and ranges from carbon nanotubes to freestanding diamond windows. A focus area is the fabrication of microelectromechanical systems (MEMS) and micro components for applications such as sensors. CCL also provides access to coating equipment to its customers. Diamond and diamond-like materials are synthesized using in-house developed plasma assisted chemical and physical vapor deposition technologies. Several areas of expertise and research are listed below.

Diamond and Diamond-Like Carbon (DLC) Products, Coatings, Coating Equipment and Engineering Services

- Synthetic diamond materials: crystals, windows, heat spreaders, foils
- Boron (p-type) and phosphorous (n-type) doped diamond electrodes

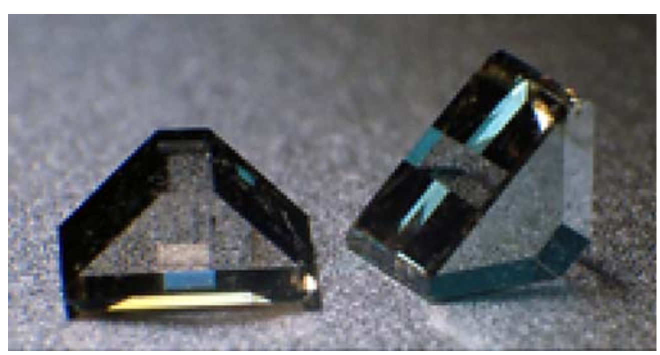

FIGURE 2. Optical diamond crystals.

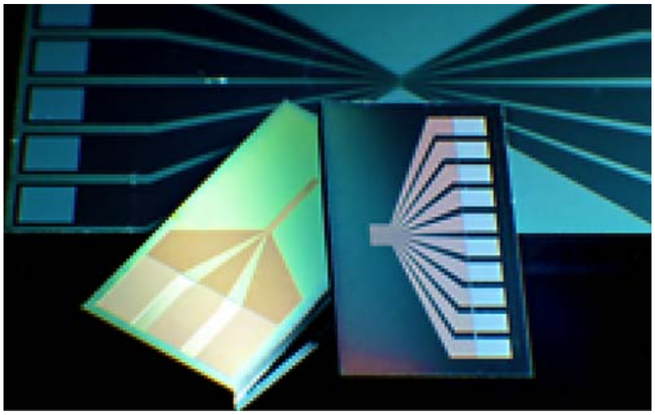

FIGURE 3. Diamond micro electrode array chip.

- Diamond material MEMS integration and micro-fabrication
- Synthetic diamond coatings
- Diamond-like carbon (DLC) coatings and equipment
- Contract research, development and testing services

Electrically Conductive Diamond Electrodes

Boron doped diamond (BDD) is an excellent electrode material with a large potential window in aqueous solution and low background current. The wider potential window and lower background currents make the BDD material very attractive for electrochemical analysis experiments. Reactions occurring in potential ranges from about –0.5 V to –1.2 V and about +1.8 V to 2.5 V can now be analyzed which is impossible with traditional electrode materials such as Au and Pt. The lower background current allows for higher sensitivity and lower detection limits.

Apart from its large potential window and low background currents boron doped diamond exhibits high chemical and electrochemical stability. BDD is mechanical robust and biocompatible which makes the material a suitable electrode material for various applications such as:

- Water and waste water treatment (oxidation of organic contaminants)
- Water disinfection (ozone production on electrode surface)
- Production of strong oxidizers
- Bioelectrochemical applications
- Electroanalytical applications

Diamor (Diamond Like Carbon-DLC) Coatings and Processes

The DLC coatings capabilities include:

- Superhard amorphous carbon coatings (ta-C)
- Hydrophobic amorphous carbon coatings (ta-C:F)
- Nitrogen doped amorphous carbon coatings (ta-C:N)

These coatings are applied using a laser-arc equipped physical vapor deposition machine. The applications of the coatings include:

- Wear coatings for tools and components (e.g., cutting tools, aluminum forming rolls)
- Wear coatings for engine parts (e.g., piston pins, piston rings, gears, pins, etc.)
- Dry lubricant hard coating for machinery
- Non-stick coating for forming tools
- Biocompatible coatings for medical instruments and implants
- Optically transparent hydrophobic coatings for plastic materials
- Optically transparent hydrophobic coatings for solar cell and display protection

FIGURE 4. *Left to right:* coated engine parts, coated forming tools, and coated micro drills.

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