Laboratory for Electromagnetic and Electronic Systems

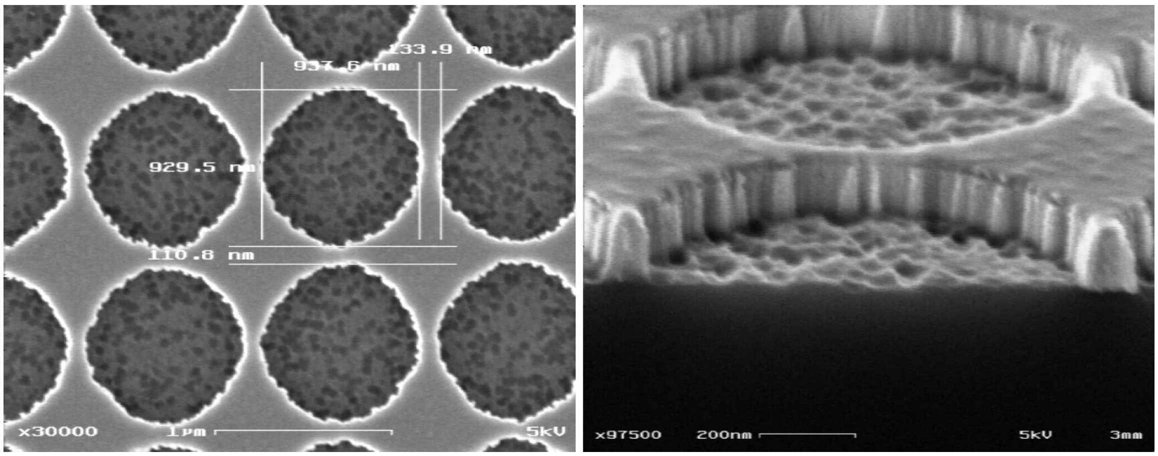
The mission of the Laboratory for Electromagnetic and Electronic Systems (LEES) is to be the focus for research and teaching in electric energy from its production through its processing to its utilization, and in electromechanics from the macroscopic through the nanoscopic levels. Electric energy and electromechanics are defined broadly to include power systems monitoring and operation; automatic control; power electronics; high-voltage engineering; and conventional, continuum, and biological electromechanics. Much of the work of the laboratory is experimental, and industrial sponsorship represents a large fraction of its support. The laboratory's professional staff consists of 8 faculty members from the Department of Electrical Engineering and Computer Science (EECS), 1 principal research engineer, 1 principal research scientist, 1 postdoctoral associate, and approximately 50 graduate students. The laboratory faculty and most of the staff are heavily involved in both undergraduate and graduate teaching. Faculty from the Departments of Mechanical Engineering, Chemical Engineering , and Materials Science and Engineering are collaborators in many of the laboratory's programs, and there are extensive joint activities with the Microsystems Technology Laboratory, the Gas Turbine Laboratory, the Materials Processing Center, the Laboratory for Information and Decision Systems (LIDS), and the Harvard–MIT Division of Health Sciences and Technology (HST).

Automotive Electrical and Electronic Systems

Laboratory research on automotive electrical systems is funded principally by the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, directed by principal research scientist Dr. Thomas Keim. Further funding comes from the Toyota Corporation, the Draper Laboratory, the Bosch Corporation, and a grant from the Sheila and Emmanuel Landsman Foundation.

Principal research engineer Dr. Chathan Cooke and Dr. Keim have been working with graduate student Vasanth Sarathy on the impact of electrochemical processes on the degradation of printed circuit boards, such as used in automotive electronics. The effort is directed at identifying and quantifying physical models for the degradation processes that lead to failures and means to test for reliability. Clear evidence for Arrhenius-type thermally activated electrochemical processes has been confirmed, and ion-specific phenomena are under investigation. Testing procedures to better quantify circuit-board reliability also face challenges from new materials (such as lead-free systems) that are required for ecofriendly products. These test models and processes are thus also intended to improve new product development.

Professors John Kassakian and Joel Schindall and graduate student Alejandro Dominguez-Garcia are working on the critical reliability considerations that are evoked when X-by-wire systems (steer-by-wire, brake-by-wire, throttle-by-wire, etc.) are utilized for automotive control. These systems offer great promise but cannot be fielded until architectures can be developed that yield near-perfect reliability without requiring the high redundancy and cost associated with aerospace-type configurations. To address this challenge, they have proposed some independent backup actuator mechanisms. Initial modeling and characterization of these mechanisms indicate the potential to make X-by-wire feasible in automotive applications. The research is also developing an improved Markov-based system description language to permit unambiguous characterization and analysis of the complex, reconfigurable fault-tolerant systems that are required to meet these types of performance constraints. This work is receiving collaborative and financial support from the Draper Laboratories via their Industry IR&D support program, and it is also receiving some support from the Bosch Corporation.



Silicon substrate with patterned tungsten (100nm) and chrome (30nm) layers forming a 2D photonic crystal on the surface.

The thermophotovoltaic (TPV) power generation research program has achieved significant milestones since last year. The project team consists of Professors Kassakian, Schindall, and David Perreault, along with Dr. Keim and doctoral students Ivan Celanovic and Natalija Jovanovic. A fabrication process has been developed and validated to produce the selective emitter structure designed, analyzed, and simulated last year. Initial results using a sputtered tungsten substrate have yielded a grid of 0.9 micron holes with a periodicity of 1.0 microns. A scanning electron micrograph of the structure reveals the vertical cell walls resulting from the anisotropic tungsten etch. The next milestone is to fabricate a deep-hole (c. 1 micron) structure on single-crystal tungsten.

The TPV program has also produced the discovery of what we call a vertical-cavity enhanced resonant thermal emitter (VERTE). The VERTE is a quasi-monochromatic, partially coherent thermal source that holds great promise for a range of applications from highly efficient TPV systems to near–IR and IR sensors. One of its salient features is a spatially narrow and highly directional beam of radiation.

The laboratory’s unique electromechanical engine valve design continues to make progress under the efforts of Dr. Keim, Professors Kassakian and Perreault, doctoral student Yihui Qiu, and UROP students Matt Angle and James Otten. We have shown that a control that follows the frictionless ballistic trajectory of the valve is much more efficient than the originally designed sinusoidal trajectory. A new slot-cam has been designed, and the motor is being replaced by a smaller design that is closer to a practical implementation.

The laboratory's work on advanced automotive alternators has continued to advance over the last year. Professors Lang and Perreault, Dr. Keim, and graduate student Leandro Lorilla have demonstrated the viability of new construction and power electronic control methods for the field windings of automotive Lundell alternators. These new methods provide significant improvements in alternator power density, efficiency, and transient control and are compatible with and complement the other advances in alternator design that have been made by the laboratory. The efficacy of these new methods has been demonstrated under laboratory conditions, and construction and test of a complete alternator implementation is in progress. This work has resulted in two issued patents and three journal publications in the last year, with additional publications pending.

Professor Markus Zahn, Dr. Keim, and graduate student Matthew Mishrikey completed a project successfully demonstrating a simple, inexpensive device capable of detecting the presence of an electrical arc in an automotive wire harness.

Modeling, Monitoring, and Control of Power Systems

Professor George Verghese and Dr. Bernard Lesieutre of Lawrence Berkeley Laboratories, along with recent doctoral graduate Dr. Ernst Scholtz (now at ABB), have developed observers and observer-based fault detection schemes for the swing dynamics of power networks. A paper on this has been accepted for the 2005 Power Systems Computation Conference. They have also developed designs for novel controllers that exploit the wave nature of (electromechanical) swing disturbances in power systems; these results are garnering attention for their novelty as an approach to controlling power network dynamics.

With recent graduate student Teruo Ono, who has returned to Tokyo Electric Power Company after receiving his master's degree from MIT, Professor Verghese has developed assorted approaches to understanding the dynamics of competing adaptive agents in small power markets.

Professor Verghese and his students have also been studying general dynamical networks, with power systems as a motivating example. His graduate student Laura Zager completed a master's thesis examining notions of graph similarity in domains such as bioinformatics, structural chemistry, image analysis, and the web. She developed a new measure of graph similarity that assigns similarity scores to all combinations of, respectively, nodes with nodes and edges with edges in the two graphs being compared, and she has applied this measure with good success to problems of graph matching.

Another of Professor Verghese's graduate students, Victor Preciado, is working toward a doctorate in the area of complex nonlinear networks and has new results on synchronization in random networks. These results are based on analytical computations of the moments of the eigenvalue distribution for the Laplacian matrix that governs the network. His random networks have fairly richly parameterized structures, which might enable them to model real-world networks more closely.

During the past year, Professor Steven Leeb and graduate student Robert Cox, in collaboration with several US Coast Guard officers, conducted field studies of the power system onboard the USCGC *Seneca* stationed in Boston. Using a newly developed version of the nonintrusive load monitor (NILM) as a data collection and analysis platform installed on the *Seneca,* the team detected and identified faults on board the ship, including a severe leak in the ship's vacuum system and a coupling failure in the auxiliary seawater pumping system. These observations have led to the development of diagnostic metrics that should show improvement in operational readiness of the vessel and similar ships during the coming year. Additional work began this year to extend the NILM for use as a diagnostic platform on board larger US Navy vessels, including the DDG-51 class of destroyers.

Professor Leeb and Mr. Cox have also developed new electronic transceiver technology this year for tracking air flow in buildings. This technique takes advantage of the small quantities of ozone generated by high-voltage power electronic circuits. It can be used to track air flow in near real-time in buildings, both for energy efficiency and occupant comfort and also potentially to track and mitigate airborne threats released in a facility.

Dr. Cooke and graduate student Jose Mendez-Alcazar have been exploring the use of electric power cables, such as those supplying power to motors, for carrying control and position data. The "data-over-power" approach reduces costs and enhances flexibility. The initial work has been to better quantify the wave propagation properties of motor power cables. Means to couple data into and out of the cable are also under investigation. It is planned to build and operate a demonstration system on a motor driven by a pulse-width modulated inverter.

Dr. Cooke, working with the electric power apparatus industry, has applied ultrasonic diagnostics to quantify space charges and internal stresses in high-voltage epoxy dielectrics. This work has been extended to create a simultaneous thermal and electrical gradient. These multistress test results have recently shown that such gradients induce conduction-driven space charges and enhanced internal fields. Measurement values are being compared to theoretical values to establish a clear model for stress-induced conduction. The purpose of this effort is to improve the long-term reliability of materials used in electric power systems and other high-voltage applications.

Power Electronics and Electromechanics

Professor Perreault and graduate students Juan Rivas, Yehui Han, David Jackson, and Olivia Leitermann have continued development of very high frequency power electronic circuits. These new circuits provide dramatic increases in the achievable switching frequency of power electronic circuits. Such increases are central to achieving miniaturization and integration of power conversion electronics. Advances this year include the development of methods for achieving wide operating ranges in radio-frequency power converters and new circuit designs having greatly improved power density. These new techniques have been demonstrated in power converters operating at switching frequencies up to 100 MHz, more than an order of magnitude higher than state-of-the-art commercial designs. In parallel with this effort, Professors Perreault and Lang and former LEES graduate student Dr. Joshua Phinney have continued their development of integrated passive power components that scale well to small sizes and high frequencies. Advances this year include the development of analytical and computational means for modeling and designing integrated LC–passive components. The use of these multiresonant LC components in the design of radio-frequency power amplifiers has also been explored and demonstrated experimentally. Together, these efforts have resulted in a patent application, a provisional patent application, and two publications this year.

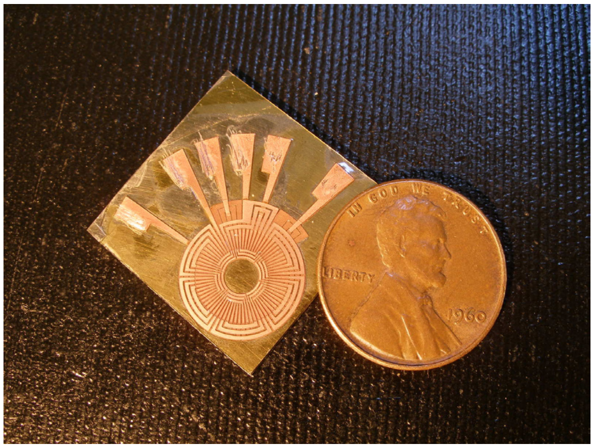
Professor Perreault, graduate students Daria Lymar and Brandon Pierquet, and former LEES graduate student Dr. Timothy Neugebauer have continued their development of electromagnetic filters and components with compensated parasitics. This year they developed new electromagnetic interference filters that achieve high performance at substantially reduced size and cost by compensating capacitor and inductor parasitics. Moreover, a new coupled magnetic filter method providing adaptive parasitic cancellation has been developed and applied to the design of a switching power converter. These new filter techniques provide factors of 5 to 30 increases in performance over conventional designs and are expected to find wide use in power-filtering applications and in power converters. This work was the subject of a patent filing, a second patent disclosure, and two publications this year.

Professors Leeb and Kirtley taught the first offering of a new power electronics laboratory class for undergraduates. This hands-on course was introduced to 21 students in a pilot offering last year. The course was successful and accepted for regular fall teaching as the new EECS course 6.131. It is expected to serve an interdisciplinary community of students including EECS and Mechanical Engineering students.

Sensors, Nanotechnology, and Microelectromechanical Systems

As part of the MIT Micro Gas Turbine Engine Project, Professor Lang and former graduate student Dr. J. Lodewyk Steyn, in collaboration with Professor C. Livermore of Mechanical Engineering, have fabricated and demonstrated a combined microelectromechanical systems (MEMS) electric induction generator and gas turbine that is designed to produce watt-level electrical power from a compressed gas source. During the past year, tests to demonstrate electrical self-excitation were successfully run, and the generator produced a net power of approximately 0.2 mW; the excess output was used to power light-emitting diodes. This is the first known demonstration of a self-excited electric (as opposed to magnetic) induction generator on any size scale and represents the largest known power output from an electric MEMS generator.

Also as part of the MIT Micro Gas Turbine Engine Project, Professor Lang and graduate student Sauparna Das, in collaboration with colleagues at the Georgia Institute of Technology, have fabricated and demonstrated MEMS permanent-magnet synchronous generators designed for use with microgas turbines. These generators have produced an electrical output power of nearly 2 W. This is the largest known power output from any MEMS generator. Tests at higher power levels are currently under way.



The size of a second-generation surface-wound stator for the microscale permanent-magnet generator is measured by a penny.

Professor Lang and graduate student Bernard Yen have designed and demonstrated a macroscale vibration-to-electric energy harvester. The harvester, based upon a vibrating variable capacitor, has produced approximately 1 mW of electrical power.

Professor Zahn has continued his magnetic fluids research, exploring new behavior and applications of ferrofluids in rotating magnetic fields. These fields cause the magnetic nanoparticles to spin due to a magnetic torque on the fluid resulting from the magnetization and the magnetic field being in different directions. Such suspensions of spinning magnetic nanoparticles act like nanosized gyroscopes that stir and mix the fluid. This is useful in microfluidic and nanofluidic applications or for heat generation due to viscous dissipation of spinning nanoparticles.

Nanotube-Enhanced Ultracapacitor

Double-layer or ultracapacitors are electric field energy storage devices that use highly porous activated carbon to form high surface area electrodes. This large area in conjunction with the small ionic charge separation at the surface creates a capacitor having an extremely high effective capacitance. Professors Schindall and Kassakian, doctoral student Riccardo Signorelli, and UROP students Catarina Bjelkengren, Diana Cheng, and Benjamin Cooper have been working to synthesize a structure where the activated carbon electrode coating is replaced with an ordered array of vertically aligned, single-walled carbon nanotubes. This structure results in a predicted energy storage density (>150 Wh/kg) that is comparable to or higher than the lithium-ion battery. In addition, the low contact resistance between active layer and current collector, combined with the ballistic transport exhibited by the nanotubes in the electrode structure, results in a predicted power density more than two orders of magnitude higher (>100 kW/kg) than either batteries or fuel cells. During the past year, we have constructed the high-temperature, low-pressure vapor deposition furnace required for this nanotube growth and have successfully produced representative patches of vertically aligned nanotubes. We have been awarded ongoing funding for this activity by the Ford–MIT Alliance.

Bioelectromechanics and Biomedicine

Recently established research in Professor Verghese's group, done with postdoctoral associate Dr. Thomas Heldt in LEES and also in collaboration with Professor Roger Mark of EECS/HST and Professor Peter Szolovits of EECS/CSAIL under a new National Institutes of Health grant, addresses model-based data integration and reasoning for patients in intensive care units. The LEES part of this research involves working with electrical circuit analogs for cardiovascular dynamics, addressing issues of modeling, model simplification, and identification. The recent master's thesis by Carlos Renjifo (now at the Applied Physics Laboratory in Baltimore) developed approaches to understanding and tracking—in both the time and spectral domains—multichannel ICU data. Also completed recently is the master's thesis of Zaid Samar (now at Oracle) on dynamic simulation and identification for cardiovascular data from the ICU. Doctoral student Tushar Parlikar has developed averaged models for cardiovascular dynamics, and these results will be presented at the 2005 IEEE Engineering in Medicine and Biology Society's annual conference (EMBS'05). He is currently building on these models to develop adaptive observers for cardiovascular dynamics.

Professor Verghese, in collaboration with Professor Peter Doerschuk of Purdue University and Professor Sanjoy Mitter of EECS/LIDS, supervised the recent master's thesis of Mr. Keyuan Xu on a simulation environment for evaluating Markov models of sequence evolution in biology. The thesis won the EECS department's Guillemin Award for Outstanding Master's Thesis, and a paper on the topic of the thesis has been accepted for presentation at EMBS'05.

Professor Zahn's ferrofluids research has led to a collaboration with EECS colleague Professor Elfar Adalsteinsson and has resulted in the preparation of a patent application related to biomedical applications with magnetic resonance imaging (MRI). One embodiment concerns modulation of the applied rotating magnetic field to change the ferrofluid magnetic susceptibility tensor and thereby modulate MRI contrast to cause a "twinkling" effect so that the location of the magnetic nanoparticles can be more easily detected. If the nanoparticle has a functionalized surface coating selectively adsorbing to specific media, such as a tumor, we can use the MRI twinkling to identify the location of the tumor, which can then be treated with the help of magnetic nanoparticle heating. Our eventual goal is in vivo imaging of targeted delivery and monitoring of remotely induced hyperthermia as a cancer therapy. Other uses might include enhancing drug efficacy or mediating drug delivery through magnetic field manipulation of magnetic nanoparticles.

New Appointments and Promotions

Professor Schindall was appointed associate director of LEES, succeeding Professor Lang. Professor Verghese was appointed EECS education officer. Professor Leeb was promoted to full professor.

Honors and Awards

Professor Perreault received the Ralph R. Teetor Educational Award from the Society of Automotive Engineers for contributions to teaching, research, and student development.

Professor Perreault was named the first Emanuel E. Landsman career development associate professor of electrical engineering and computer science.

Graduate student Keyuan Xu won the EECS department's Guillemin Award for Outstanding Master's Thesis.

Graduate student Shihab Elborai received the EECS Carlton E. Tucker Teaching Award for excellence in teaching.

John Kassakian
Director
Professor of Electrical Engineering

More information about the Laboratory for Electromagnetic and Electronic Systems can be found online at http://lees.mit.edu/lees/.