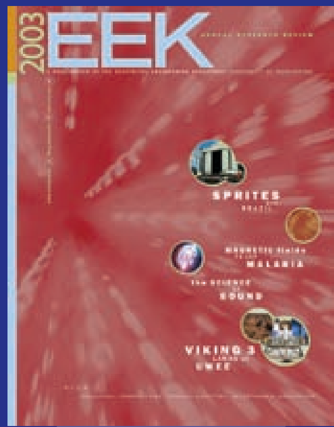
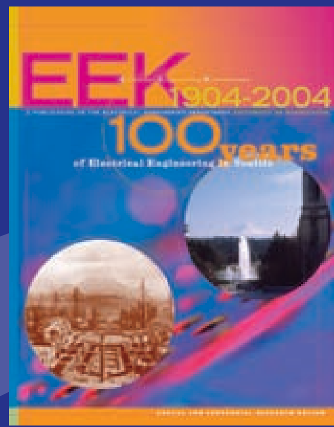
eeK 10

electrical engineering kaleidoscope

A Publication of the Electrical Engineering Department | University of Washington

(Annual Research Review)





EEK is turning 10!

It is therefore appropriate as a moment of reflection on the past as well as a point of renewal and looking forward.

During this period, EEK has garnered several awards as a publication including the CASE District III Bronze Award for the 2004 issue, and the Silver Award for the 2008 issue.

EEK was started as a showcase of the diversity of research and innovations within the department and I hope you have enjoyed keeping up with the changes over the years within the EE community. With the passing of the Editorial mantle, comes an opportunity for some new ideas. While maintaining the core mission of serving as a reflection of the current research via student-centered articles, we intend to broaden EEK content to embrace associated outreach goals. For example, we plan to highlight key relationships with our industrial affiliates and partners that positively impact the evolution of our research and education missions, as well as the distinctive accomplishments and contributions to technology leadership and creative engineering by our alumni. We are delighted by the Diamond Award (2010) bestowed on our alumnus Richard Citta; please see the back inside cover for our recognition of a career marked by exceptional achievement in TV engineering.

The first decade of the 21st century is now in the books, and at the time of writing, the national mood is not one of optimism. In particular, higher educational institutions are facing increasing budgetary constraints. But as always, seeds of the next innovation reside among the current challenges. There are many exciting prospects for EE in the coming decade, many centered around our ability to contribute to the great global problems of our time. Notable among them is the increasing confluence of traditional EE sub-disciplines with emerging Nano-Bio technologies, and EE's role in contributing to solutions confronting the most important 'networks' (energy, transportation, global climate, health and socio-economic stability) that underpin our civilization.

Happy reading and here's to the next 10 years of EEK! — SUMIT ROY
EEK Faculty Editor

PUBLISHER

Electrical Engineering Department of the University of Washington

Leung Tsang, Chair
Sumit Roy, Associate Chair for Research & Development
James A. Ritcey, Associate Chair for Education

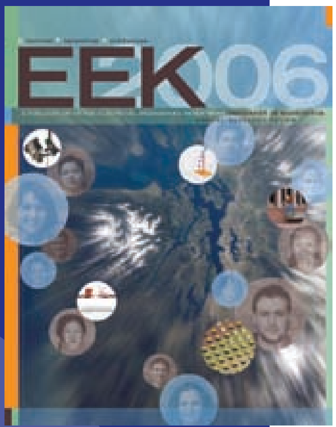
DESIGN

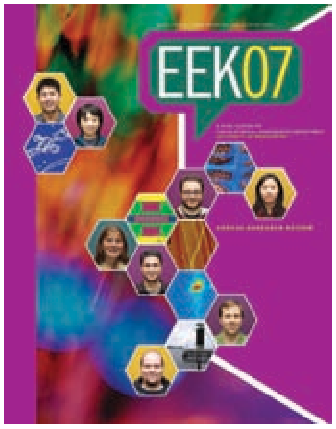
Sarah Conradt, Designer

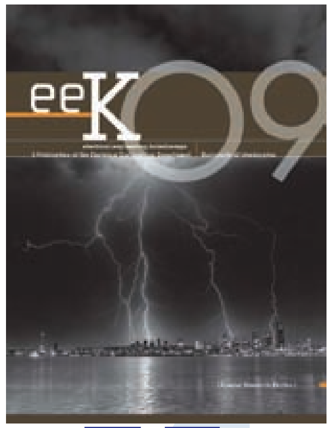
EDITORIAL STAFF

Sumit Roy, Faculty Editor
Laura J. Haas, Staff Editor

Print management by University of Washington Creative Communications







eeK10

(Annual Research Review)

this issue...

STUDENT RESEARCH

FACULTY PAGES

WELCOME TO eeK10

This year, we are celebrating the tenth anniversary of EEK. I would like to extend a special thank you to Professor Howard Chizeck for his nine years of dedicated service as EEK's faculty editor and the vision he created for this publication. When we review the research progress in the EE department over the last decade, we witness the transition from traditional electrical engineering subjects to multidisciplinary collaborations, and to new applications in biology, health sciences and medicine. Professors Babak Parviz and Brian Otis received the NSF Emerging Frontiers in Research and Innovation Grant to construct a functional contact lens that incorporates electronic biosensors and monitors biomarkers on the surface of the eye. Professor Michael Hochberg received the 2009 Presidential Early Career Award (PECASE) for his work in silicon nanophotonics. He is presently installing the multi-million dollar electron beam lithography tool. Professor Shwetak Patel's work to incorporate electrical, gas, and water sensors in a unified technology for buildings has attracted national attention.

As we continue to be at the forefront of emerging and interdisciplinary research areas, we also remain committed to EE's core discipline areas as we are actively recruiting for the Close Chair Professorship. The ideal candidate will have an expertise in smart grids and sustainable energy systems, and will rejuvenate the department's energy research program, spawning a new generation of promising research technologies and advancements for the next decade to come.

— LEUNG TSANG

Chair and Professor

Department of Electrical Engineering

Power Saving Strategies
for Two-Way, Real-Time Enabled Cellular Phones

JESSICA J. TRAN — Graduate Student (EE)

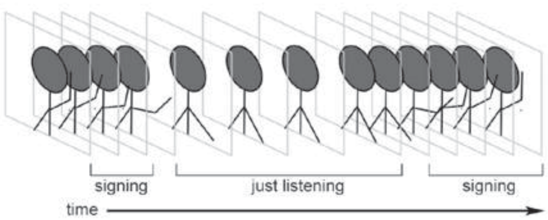
Cellular phones have become the most popular and widespread portable technology. However, the United States cellular network does not support real-time video conversations. This does not allow people in the Deaf and Hard of Hearing community to communicate in their native language of American Sign Language (ASL).

The MobileASL project has developed software to transfer real-time video on the cellular network. The current MobileASL software transmits 12 frames per second (fps) which consumes 99% of the phones' CPU. Therefore, transmitting and encoding video results in high power consumption rates which drastically deplete a full battery charge of 40 hours to 2.5 hours.

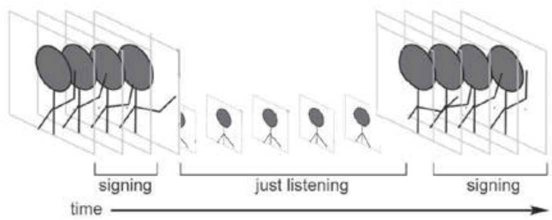
This research investigates different power saving strategies for two-way, real-time video enabled cellular phones. Since an ASL conversation involves turn-taking (times when one person is signing while the other is not), the conversation can be divided into two parts: signing and not signing. The encoding algorithms are applied to the not signing (i.e. "just listening") portions of a conversation to save computational resources.

The three different encoding algorithms applied during the "just listening" portions of a conversation are: variable frame rate (VFR), variable spatial resolution (VSR), and the combination of variable frame rate and spatial resolution. When VFR is implemented, the frame rate is reduced to one fps, which results in a "choppy" video. The VSR algorithm downsamples the "just listening" video frames to 25% of the original size, which results in a "blurry" video. Finally, a combination of VFR and VSR produces both choppy and blurry video. Measuring the battery, current drain, and CPU usage of the phone has shown that VFR and VSR both prolongs the battery life by 20 minutes and lowers the CPU usage to 33%. Finally, the combination of VFR and VSR extends the battery by 30 minutes and lowers the CPU usage to 10%.

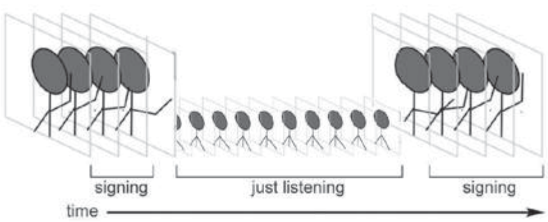
The next stage of this project will investigate which algorithm implementation is preferred by users. A web-based user study will be conducted to determine if MobileASL users are willing to sacrifice video quality to prolong the battery life of the phone.



An example of VFR implementation. The frame rate decreases when the signer is not signing (just listening), and the result is a "choppy" video.



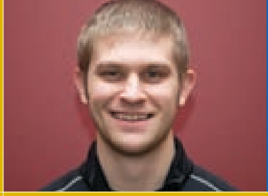
A combination example of VFR and VSR implementation during "just listening" frames. The result is a combination of "blurry" and "choppy" video.



An example of VSR implementation. The not signing (just listening) frames downsample to 25% of the original frame size, and the result is a "blurry" video.

An example of an input frame downsampled to produce a "blurry" frame.

FACULTY ADVISORS: **Eve A. Riskin (EE) & Richard E. Ladner (CSE)**
RESEARCH AREA: **Video Compression**
GRANT/FUNDING SOURCE: **National Science Foundation**



Using a Musician's Movement as a Control Signal for Audio Performance

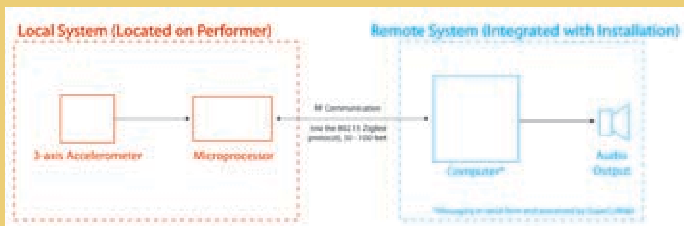
ROBERT GAY — Undergraduate Student (EE & DXARTS)

Musicians throughout history have yielded an increasing number of ways to interact in an interesting manner with their medium. Experimental approaches to audio performance can be found in a wide variety of musical genres, from Popular Rock to the Avante Garde. The purpose of this interdisciplinary project is to devise a dynamic system that can use an artist's body movement as a control for altering real-time audio. The design is aimed at being simple, affordable, and effective, allowing it to be used in a variety of performance applications, including audio installations, dance performances, and even the modern rock concert.

The original design intent for this motion-tracking system was to expand upon the "Speaker Performing Kiosk," an audio installation developed by Nicolas Varchausky at UW's Center for Digital Arts and Experimental Media (DXARTS). Upon success, the system could be very useful for both this audio installation, and for future installations and performances.

UW DXARTS graduate student Nicolas Varchausky performing in his "Speaker Performing Kiosk" at the Chapel Performance Space in Seattle, WA.

The most recent iteration of the design utilizes the output of small, tri-axis accelerometers that can be discretely placed nearly anywhere on the body from which the musician would like to gather feedback. A local microprocessor located at the hip transmits this movement information from the accelerometers at a range of 50-100 feet to a remote computer via radio frequency. These values are then collected in control buffers in the remote computer by SuperCollider, a real-time audio synthesis programming language. Both velocity and acceleration information from the body can be collected for the musician's use. The control buffers are then read back immediately and used for alteration to a wide variety of audio parameters, including altering frequency content, amplitude, or spatial orientation of a chosen audio source.



The high-level block diagram of the system's signal path.

The system's prototype has been nearly completed, where wired communication between the accelerometer and SuperCollider has been established, and real-time synthesis has been achieved. The next step is to add the wireless component of the project and develop algorithms for conditioning the signal for use in a wide variety of situations, where all types of RF interference in live situations must be considered. Following this, a final iteration will then be fabricated, which will be more physically robust, reliable, and able to withstand the pressures of live performance. An extension of this research could then be to integrate the communication of the accelerometers' values through the Musical Instrumental Digital Interface (MIDI) protocol and provide a bundled installer to a user, allowing this device to be used easily with common multi-tracking and live performance commercial software.

FACULTY ADVISOR: **John Sahr**
COLLABORATORS: **Nicolás Varchausky, Graduate Student (DXARTS)**
RESEARCH AREA: **Sensing Systems & Signal Processing in the Arts**

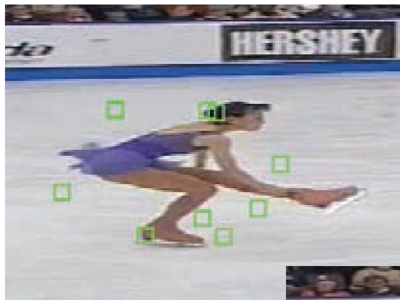
Action Classification
Using Space-Time Link Analysis

HAOWEI LIU — Graduate Student (EE)

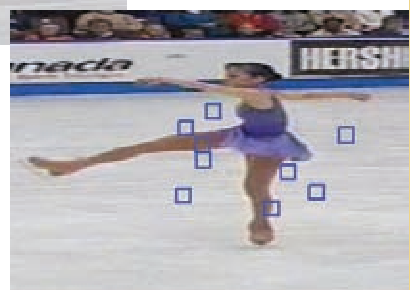
The ability to automatically detect activities from surveillance video has become an important topic and attracts many researchers in the computer vision community. A solution to this problem will not only facilitate an automatic video surveillance system, but will also improve applications such as video retrieval or summary, and human-machine/robot communication.

The difficulties are manifold as the target activity in surveillance video could come with cluttered background, camera motion, occlusion, and geometric and photometric variability. Existing methods typically ignore the spatial-temporal relationships between extracted video features, but the approach in this research is based on link analysis. By applying link analysis techniques in the space-time domain, the spatial-temporal relationships between the video features can be taken into account, while leveraging the power of graph matching for action classification.

This approach starts with the extraction of video features using a spatial-temporal interest point detector, but instead of building a codebook and histograms as other approaches do, graph matching is performed to build a network that encodes the similarities between the video features. PageRank, a link analysis algorithm, is used to mine distinctive features with respect to each action. The intuition behind this is that features have different importance. Also, distinctive features for the same action would be similar to one another and tend to interconnect through strong links in the network while only weak links would exist between features from different actions. Clustering is then done based on these mined features.



C

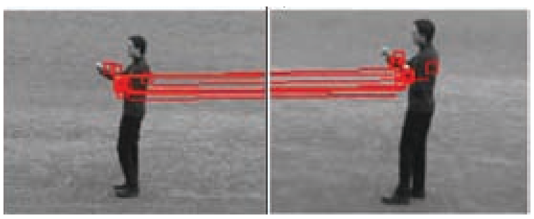


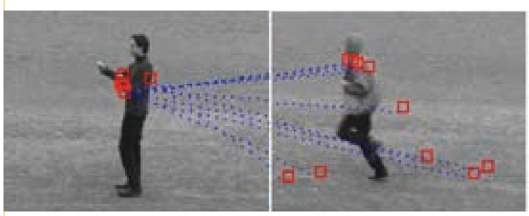
D

Mined features using PageRank for sit spin (C) and stand spin (D).

We demonstrated the use of this technology to avoid fraud in retail stores. This approach is also evaluated on two standard datasets demonstrating that the technology is capable of handling cluttered backgrounds, activities with subtle movements, and video data from moving cameras. Future work will extend this approach to localize multiple activities at different granularities.

A





B

The matching result between two sequences from the same category (A), and different categories (B). Solid lines indicate matching pairs with low cost while dotted lines indicate costly matching pairs. The matching creates a clustering effect where strong links would exist between sequences from the same category.

FACULTY ADVISOR: Ming-Ting Sun
COLLABORATORS: Dr. Rogerio Feris (IBM T.J. Watson Research Center, New York), Professor Volker Krueger (Aalborg University, Denmark)
RESEARCH AREA: Computer Vision
GRANT/FUNDING SOURCE: IBM Faculty Award

Exploiting Parsimony:
How to Find Low-Rank Matrices & Sparse Signals

KARTHIK MOHAN (EE) & DJ KRISHNAMURTHY (CSE) — Graduate Students

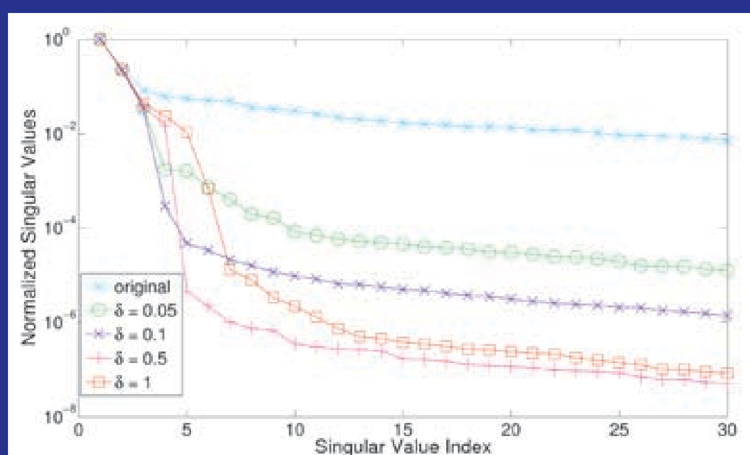
When interacting with the physical world, one typically obtains limited measurements of objects, such as an image, data matrices, or dynamical systems. When is it possible to recover the original object accurately and efficiently from linear measurements? With "Compressed Sensing" techniques, a small number of measurements (far less than Nyquist samples) are indeed enough for recovery if the sensing scheme satisfies certain properties, and more importantly, if the signal has a sparse representation in some domain (Fourier, wavelet, etc.).

This work vastly extends the compressed sensing framework and its theory beyond sparse signals by considering the problem of finding a low-rank matrix X that is consistent with measurements A(X) = b, where A is a linear map. This problem is computationally intractable (NP-hard), and arises in many applications including collaborative filtering (e.g., the well-known Netflix problem), system identification in control and computer vision, and low-dimensional Euclidean embedding (e.g., graph visualization, data dimensionality reduction). Many heuristic approaches have been used, but generally very little is known about whether they would succeed.

One popular heuristic minimizes the nuclear norm (the sum of singular values) of the matrix instead of its rank based on a property requiring A to act roughly like an isometry on low-rank matrices. In this work, noting that the ability to recover X does not depend on A itself but only on its null-space, researchers are able to develop a simple, direct condition on the null-space where nuclear norm minimization is guaranteed to succeed. This condition holds with high probability for a common class of random maps. Future work will extend this analysis to handle structured constraints arising in practice.

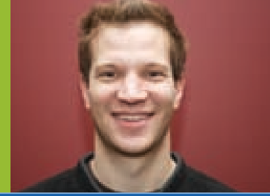
The nuclear norm heuristic can be elegantly refined to further reduce the rank of its solution by using a weighted norm and iterative weight updates. Stronger performance can be proven for this refinement (e.g., tighter bounds on the recovery error when the measurements are noisy, and A satisfies the isometry property mentioned above). The reweighted heuristic works effectively in practice as observed in a system identification application.

Current work focuses on matrix rank minimization, but the ultimate goal is to develop theory and algorithms that handle different notions of parsimony (e.g., signal sparsity, matrix and tensor rank, manifold dimension) in a unified manner motivated by real applications.



The reweighted heuristic helped identify a low-order dynamical system consistent with measured input-output data. This plot shows the decay in the singular values of the appropriate Hankel matrix. A sharper drop indicates a better description of rank of the Hankel matrix and thus the order of the system.

FACULTY ADVISOR: Maryam Fazel
RESEARCH AREA: Optimization & Control, Compressed Sensing
GRANT/FUNDING SOURCE: National Science Foundation



Microfluidic Devices for DNA and Particle Characterization

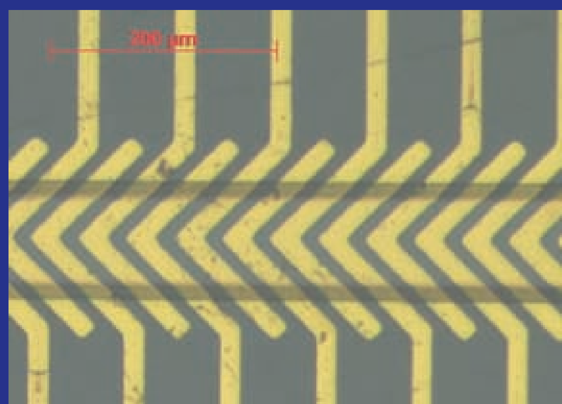
JOSEPH PEACH — Graduate Student (EE)

The goal of this research is to improve disease diagnosis through the invention and deployment of lab-on-a-chip devices using a method called dielectrophoretic field-flow fractionation (DEP-FFF). DEP-FFF uses microfabricated electrodes to generate dielectrophoretic forces in a microfluidic channel. The DEP forces redirect targets as they flow downstream, resulting in different elution times for varying targets. Targets may include cells or nucleic acids, and each may be characterized by properties such as membrane permittivity or base-pair length. The resulting chromatographic data has promising applications for disease diagnosis and genomic analysis.

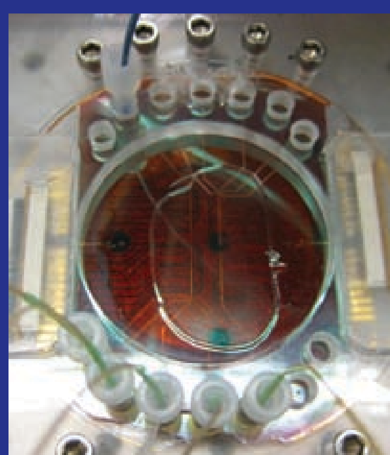
The first step towards effective treatment of infectious diseases requires rapid and accurate diagnosis. Emerging technologies such as DEP-FFF offer the ability to increase diagnostic speed and accuracy, determine the drug resistance of disease strains through molecular testing, and create point-of-care devices deployable in undeveloped regions. Using devices developed at UW EE's Photonics Lab, researchers were able to fully resolve submicron polystyrene beads of different diameters in under 15 seconds. Then, the elution profile from a DNA solution containing phiX and lambda DNA molecules allowed the presence and concentration of each molecule to be identified.

The resolution and speed obtained from these devices was improved through the use of unique electrode array configurations. One such configuration in these devices uses V-shaped electrodes to deflect and concentrate particles towards the sides of the channel. This technique is referred to as biaxial field-flow fractionation since it improves separation speed and resolution by utilizing the vertical and horizontal flow profile in the microchannel (typical field-flow fractionation devices only utilize the vertical flow profile to separate particles). A variety of additional techniques and electrode array configurations are also being tested to improve the characterization capabilities of the devices.

Future work will improve the resolution of the devices, test for new target particles, and add components to allow fast and accurate disease diagnosis. Device materials and fabrication methods will also be optimized to allow affordable deployment of the devices.

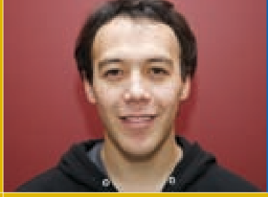


V-shaped electrode arrays were microfabricated and bonded to a cover wafer containing a microfluidic channel. The electric fields generated from the arrays selectively direct particles towards regions of different downstream velocity.



For testing, prototype devices were clamped in a custom acrylic mounting block containing machined vias for microfluidic interconnects. The active device region near the center of the devices is monitored using a fluorescence microscope. However, integrated electric components will use impedance spectroscopy for sensing and detection of particles in future devices.

FACULTY ADVISORS: Lih Lin & Vikram Jandhyala
RESEARCH AREA: Microfluidics
GRANT/FUNDING SOURCE: Washington Research Foundation & Technology Gap Innovation Fund



A Biomolecular Implementation of Linear I/O Systems

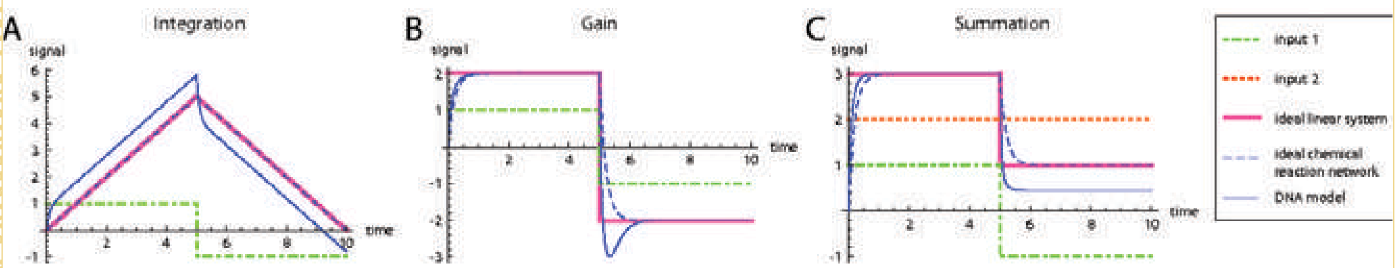
KEVIN OISHI — Graduate Student (EE)

Researchers at UW EE's Self Organizing Systems Lab are building tools and devices from fundamental biomolecular processes to interact with, control, and synthesize the behavior of biological systems. Engineered biomolecular devices are often complex, high-dimensional, and nonlinear dynamic systems that make the design of robust and composable systems difficult. This research applies tools from control theory and systems engineering to create composable biomolecular input/output (I/O) devices. Such devices enable the construction of useful and robust systems such as chemical concentration controllers, observers, and filters.

This work models and constructs approximately linear biomolecular devices. A biomolecular device is an engineered set of chemical reactions that take a concentration of signal molecules as input and produce a concentration of signal molecules as output. Devices are constructed both *in vitro* and *in vivo* from a variety of chemical substrates, including DNA, RNA, synthetic genes, and proteins. A variety of interesting devices have been constructed, however, behavior resulting from the composition of these devices can be difficult to predict due to retroactivity, the effect of downstream composition on upstream dynamics.

By engineering approximately linear biomolecular devices, well-understood tools of control theory can be exploited to engineer feedback systems which minimize retroactive effects. This research shows that any linear system can be approximated arbitrarily well using a small set of chemical reactions. Additionally, these reactions may be approximated by high fidelity model of a physical implementation using DNA as a signal molecule.

Modular components are critical to the design and control of dynamic systems. These models can be used to implement devices that reduce retroactive effects. Next steps will implement the theory *in vitro* with biochemical systems, such as enzyme-free DNA reactions, artificial genes, and fusion proteins.



Step response of the basic elements of a linear system, chemical reaction approximation, and high-fidelity DNA model. (A) Integration block. The chemical reaction model exactly implements integration. The DNA model gathers some steady-state error for each input step. (B) Gain block. The chemical reaction representation is a first-order approximation of a zero-order gain. The DNA implementation is nonlinear, and has some overshoot. (C) Summation block. The chemical reaction representation is a first-order approximation of zero-order summation. The DNA implementation is nonlinear and results in a steady state error in response to the second input step.

FACULTY ADVISOR: **Eric Klavins**
RESEARCH AREA: **Control Systems & Synthetic Biology**
GRANT/FUNDING SOURCE: **National Science Foundation**

Hydrological Modeling & Sluice Gate Control in the Mekong Delta

THO H. NGUYEN — Graduate Student (EE)

The Camau Protected Area within the Mekong Delta is surrounded by a series of sluice gates on its coastal side. The gates were designed primarily to minimize salinity invasion into the protected area. However, other stakeholders' concerns such as transportation, pollution, and wildlife sustainability also need to be taken into account. This project aims to optimize the gate operations such that all objectives are considered and to also assist hydrology managers who operate the sluice gates. The research effort provides a methodology that can potentially be much more effective in regulating water movement than the current expert prediction technique. Additionally, the research site covers 1.7 million hectares where 1.3 million hectares is farmable land. If implemented, the project findings will have a direct impact on over one million local inhabitants.

Water demand is one of many conflicting interests that need to be considered in sluice gate operation. Aquaculture (left) requires salt water while rice farming (right) requires fresh water.

From analyzing the flow network, this research proposes to separate the topologically parallel flow network into individual channels so that they can be treated individually. This separation leads to the following advantages: (1) a simple model can be used to model flow and sediment transport (i.e. salinity dispersion), and (2) significant computational savings in calculating network flow because each canal is considered individually. A simplified model to calculate water and salinity movement in each channel was developed and validated on available data obtained from local hydrology managers. Computational savings due to parallel separation and simplified modeling allows for an exhaustive search on the gate schedule (i.e. implement and compare the results of all possible gate schedule combination) to obtain the optimal solution. Since an exhaustive search is used, a globally optimal solution is guaranteed.

The next step of this investigation is to perform further analysis of the proposed method for future implementation. The findings of this project will be sent to the Mekong Delta hydrology managers for reference.

FACULTY ADVISORS: Howard Chizeck (EE) & Susan Bolton (Forest Resources)
COLLABORATORS: Cantho University College of Technology
RESEARCH AREA: Systems Control
GRANT/FUNDING SOURCE: NSF IGERT (IGERT titled, "Multinational Collaboration on Challenges to the Environment"), Fulbright Student Fellowship

Plugfest 2009:
Global Interoperability in Telerobotics and Telemedicine

H. HAWKEYE KING — Graduate Student (EE)

In the same way Internet standards have connected heterogeneous computing systems, researchers at UW EE's BioRobotics Laboratory (BRL) predict that robot communication standards will speed development and adoption of teleoperated robots. Our goal is to advance the state-of-the-art in telerobotic interoperability, focusing on the telesurgery domain.

In the long run, this will benefit surgeons and care providers who will have access to patients and colleagues around the world using their chosen equipment, patients who will access a wider range of specialists, and robotics engineers who can develop new, innovative systems that work with current teleoperation systems.

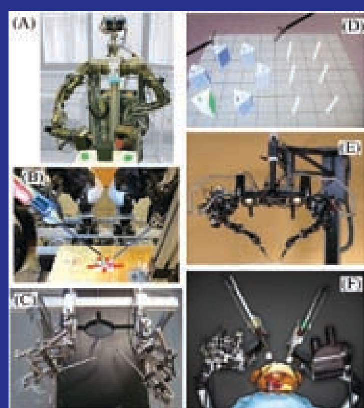
In the current work, nine, globally dispersed telerobotics groups use a common data specification, and in one 24-hour period, interoperability among 14 robotic telemedical systems was tested. The experiment is titled Plugfest 2009, and was led by the UW BRL.

Each telerobotic system was configured to use the Interoperable Telesurgical Protocol (ITP). ITP, developed by the UW in partnership with SRI International, specifies key teleoperation conventions like shared reference frame, representation of orientation, and clutching/indexing parameters. ITP data was exchanged over the Internet in low-latency UDP packets. Skype video was the only operator feedback.

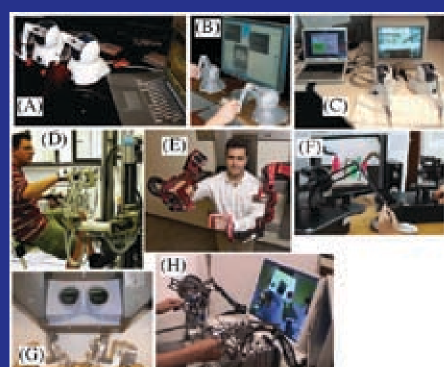
Thirty master-slave connections were attempted, and each robot was tested in at least three connections. Experimenters performed a standardized surgery-like block-transfer task with all surgical robots, or a larger-scale pick-and-place task with the general-purpose teleoperator. Success/failure of each connection was noted, results of the block transfer were recorded.

Twenty-eight successes were recorded out of 30 attempted connections. In one connection differing control loop rates on master and slave side interfered with the slave-side controller triggering fail-safe shutdown. In the other unsuccessful connection the operator to be unable to complete the task due to differences in orientation mapping between master and slave.

This experiment highlighted new techniques in human-robot interface for teleoperation, and new paradigms in telemedicine. In the BRL we continue to explore generalized interoperability among teleoperation robots, including force feedback. Also, future work will integrate the BRL robot with other surgical technology, such as imaging and simulation; bridging the gap between advanced robotics and medical applications.

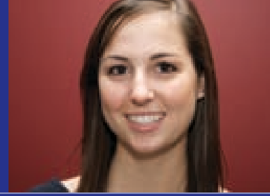


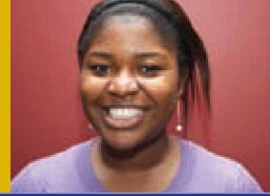
Master systems incorporated in Plugfest 2009. (A) TUM general purpose Telerobot. (B) Patient-side robot of the JHU custom version of the da Vinci. (C) TokyoTech IBIS IV surgical robot. (D) RPI VBLaST\texttrademark. (E) SRI M7 surgical robot. (F) UW Raven surgical robot.



Slave systems involved in Plugfest 2009. (A, B, C) Phantom Omni control station with free software at RPI, ICL and UW respectively. (D) TUM ViSHaRD7. (E) UCSC Exoskeleton. (F) Phantom Premium with custom software at KUT. (G) Master console of the JHU custom version of the da Vinci. (H) TokyoTech delta master.

FACULTY ADVISOR: Blake Hannaford
COLLABORATORS: Imperial College London: Ka-Wai Kwok, Guang-Zhong Yang; Johns Hopkins University: Paul Griffiths, Allison Okamura; Korea University of Technology & Education: Ildar Farkhatdinov, Jee-Hwan Ryu; Rensselaer Polytechnic Institute: Ganesh Sankaranarayanan, Venkata Arikatla; Tokyo Institute of Technology: Kotaro Tadano, Kenji Kawashima; Technische Universität München: Angelika Peer, Thomas Schauß, Martin Buss; University of California, Santa Cruz: Levi Miller, Daniel Glozman, Jacob Rosen; SRI International: Thomas Low
RESEARCH AREA: Surgical Robotics, Telerobotics, Networking
GRANT/FUNDING SOURCE: Development of the RAVEN was by US Army MRMC Grant DAMD17-02-1-0202





Haptic Characterizations of Activities of Daily Living

BRITTANY REDMOND (EE) & RACHEL AINA (CIVIL E) — Undergraduate Students

The vast majority of the activities in our daily lives involve the hands in haptic, touch interaction with tools, objects, or the environment. These "Activities of Daily Living" (ADLs) are interesting to designers of consumer products and tools, as well as researchers concerned with the self-sufficiency of the elderly and rehabilitation patients.

This research reports measurements of force and torque characteristics of ADLs involving haptic manipulation. The overall aim is to create a database that researchers can access containing measurements of physical variables characteristic of manipulation tasks in the everyday environment.

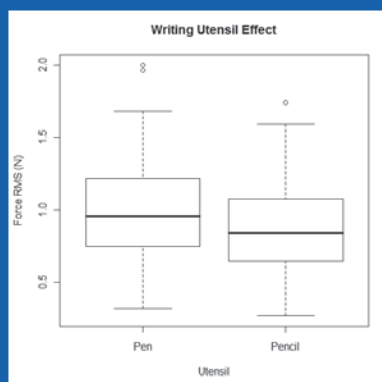
Four exemplary activities were selected from the wide variety of actions performed in daily living. The activities included: writing activity, jar activity, toothbrush activity and the cell-phone activity. Within activities, individual subtasks were identified and in total, 11 different tasks were selected. Instrumentation was designed for each activity to incorporate a six-axis force/torque sensor (ATI Inc). Users performed each task using an instrument, and three axes of force and torque were recorded to data files. The data files were analyzed using the R statistical software package to compare root-mean-squared (RMS) force and torque for each task the data was collected from.

A cell phone body modified for button force sensing. A six-axis force/torque sensor is mounted between masonite plates mounted to the back of the cell phone.

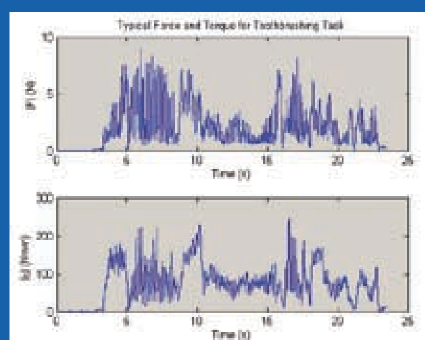
Results from the writing tasks showed that a greater force was applied when a pen was used to write with compared to a pencil. A variance analysis confirmed that the difference between a pen and pencil is statistically significant; there is less than a 5% chance that these results are random. The average force and torque RMS for each task is shown in Table I. Force RMS range from .954 to 6.37 N, and torque RMS range from 79.7 N-mm to 433.8 N-mm.

Average values of force and torque recorded in each task.

Task	FRMS (N)	TRMS(Nmm)
Writing- Pencil	0.95	N/A
Writing- Pen	1.03	N/A
Jar Open-Close	5.31	434
Tooth Brushing	6.37	79.7
Dialing Phone Number	1.70	N/A
Texting- T9	1.40	N/A
Texting- ABC	1.03	N/A



Average force levels for the writing tasks using a ball-point pen.



Typical forces and torques recorded for 20 seconds of tooth brushing.

This data is currently being packaged for an online archive which will be available to researchers across the world. The goal will be to expand this work to the medical realm by studying the forces and torques applied on surgical tools during operations.

FACULTY ADVISOR: Blake Hannaford
COLLABORATORS: Tejaswi Gorti, Undergraduate Student (EE)
RESEARCH AREA: Haptics
GRANT/FUNDING SOURCE: The National Science Foundation Research Experiences for Undergraduates Grant IIS-0713028

The Collaborative Partnership of Intel® & UW EE

Truly collaborative partnerships between industry and university are difficult to build and even more difficult to sustain over a duration. The differences behind the driving forces of shorter-term product-oriented industry and the longer-term intellectually-driven mission of academia are well known. Nonetheless, there is a logical correlation between the needs of skilled, well-trained graduates produced by universities who ultimately drive the next wave of innovation in high-tech industry. Despite the difficulties noted above, departments have constantly found ways to partner with industry in a variety of ways. In this issue, we profile one of UW EE's most comprehensive partners of long-standing: Intel Corporation.

Intel has a long history of engagement with the department on multiple fronts—from providing internships, to hiring our undergraduate and graduate students, supporting Ph.D. students via fellowships, direct support of faculty research through grants, and generous upgrading of our infrastructure for research and general purpose computing. Intel's aggregate philanthropic support to UW EE totals a little over $10 million. Intel benefits through the joint exploration of new technologies, acceleration of long-term research, and the opportunity to work closely with top students and exceptional faculty.

> "Intel is a fantastic partner for EE. The exchange of ideas and technical expertise is a two-way street that contributes to a robust research environment for electrical engineering students and faculty. Intel is one of our most important corporate partners."
>
> – LEUNG TSANG, CHAIR AND PROFESSOR OF ELECTRICAL ENGINEERING

One of the more remarkable outcomes of the UW-Intel relationship is the new model of industry–university collaboration that led to the establishment of research laboratories close to three of its top academic partners: the University of Washington, UC Berkeley, and Carnegie Mellon. Founded in 2001, Intel Labs Seattle is located only a few blocks away from the UW campus. UW students and faculty have the opportunity to work with Intel researchers on ideas with the potential to impact not only the future of the company, but also a wide range of computing and communications applications. We record our deep appreciation of Intel's long standing support of the EE department, and trust that this relationship will continue to mutual benefit for many years to come.

Continue reading to learn more about the multiple dimensions of the Intel/UW EE relationship with a spotlight on the faculty, students and Intel personnel involved.

GRADUATE FELLOWSHIPS

Intel Corporation and the Intel Foundation together support graduate fellowship programs at select universities in the United States. These fellowships are awarded to outstanding students in engineering, computer science and other technical majors focusing on semiconductor technologies, micro-architecture, software technology and design, and communications. The fellowship includes a cash award (tuition and stipend), an Intel technical liaison and travel funds to meet with the liaison. This is a highly competitive program with a limited number of fellowships awarded annually. Our graduate students continue to be successful in being honored with this award.

2009-2010 Intel Ph.D. Award Winner: UW EE Graduate Student Parmoon Seddighrad
Thesis: Energy-Efficient High-Linearity Multi-Standard RF Transmitters in Nanometer CMOS

For the 2009-2010 academic year, the Intel Corporation awarded approximately $2 million in fellowships to Ph.D. students. Fellowship recipients are Ph.D. candidates at the following universities: Carnegie Mellon University, Columbia, Cornell, Georgia Institute of Technology, Massachusetts Institute of Technology, Oregon State, Princeton, Purdue, Stanford, University of Michigan, University of Washington, University of California Berkeley, University of California - Los Angeles, University of Illinois - Urbana - Champaign, University of North Carolina, University of Southern California, and University of Texas - Austin. Beyond Intel-managed programs, the company also collaborates with the National Consortium for Graduate Degrees for Minorities in Engineering and Science (GEM) and the Semiconductor Research Corporation (SRC) to offer additional graduate fellowship opportunities.

UW EE Intel Ph.D. Fellowship Award Winners

2009-2010
Parmoon Seddighrad (David Allstot, VLSI/Embedded Systems)

2008-2009
Arun Sathanur (Vikram Jandhyala, Electromagnetics)

2007-2008
Cherry Wakayama (Richard Shi, VLSI/Embedded Systems)
Jeffrey Walling (David Allstot, VLSI/Embedded Systems)

2006-2007
Sudip Shekhar (David Allstot, VLSI/Embedded Systems)
Jean Wang (Lih Lin, Electronic Devices/MEMS)

2005-2006
Cameron Charles (David Allstot, VLSI/Embedded Systems)
Kjersti Kleven (Scott Dunham, Electronic Devices/MEMS)

2003-2004
Jeyanandh Paramesh (David Allstot, VLSI/Embedded Systems)

2002-2003
Mark Chang (Scott Hauck, VLSI/Embedded Systems)

2001-2002
Rebecca Bates (Mari Ostendorf, Signal & Image Processing)

2000-2001
Brad Gillespie (Les Atlas, Signal & Image Processing)
Alicia Manthe (Richard Shi, VLSI/Embedded Systems)

UW EE Intel IMAP Master's Fellowship Award Winners

2001-2002
Melissa Meyer (John Sahr, Signal & Image Processing)

2000-2001
Maikael Thomas (Yongmin Kim, Signal & Image Processing)

UW EE Intel Dupont Fellowship Award Winner

2002-2003
Allan Yeung (Ward Helms, VLSI/Embedded Systems)

Engineering Undergraduate Research Program participants.

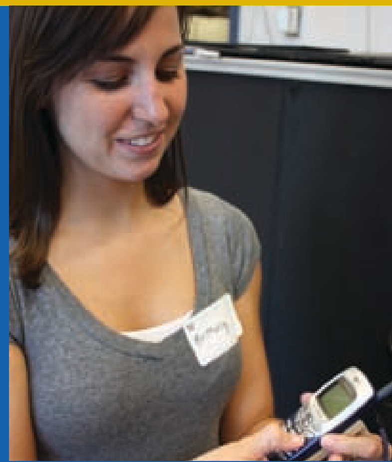
UNDERGRADUATE RESEARCH PROGRAM

The College of Engineering Undergraduate Research Program (EURP) offers opportunities to engineering undergraduate students to work with faculty and graduate students on cutting-edge research problems. Intel and additional industry partners provide funding for such undergraduate research experience and encourage students to pursue an advanced degree in engineering. The following chart lists EE faculty and students participating in the EURP.

The program launched in 2006 and to date 51 students have received research awards. Of these students, 55% are from underrepresented American populations (African American, Native American, Hispanic), and 43% are female. Perhaps the best statistic is that 59% of undergraduate research program participants are pursuing MS or Ph.D. degrees.

> "My goal is for 100% of our undergraduate students to participate in experiential learning through either undergraduate research or internships at companies. Both experiences are valuable whether a student chooses a career in industry or pursues graduate education."
>
> — MATT O'DONNELL, FRANK AND JULIE JUNGERS DEAN OF ENGINEERING

Student Name	Faculty Advisor	Project Title
Rachel Aina (IE, EE)	Blake Hannaford (EE)	Haptic & Conversation Analysis
Donald Chen (CSE)	Mani Soma (EE)	Intellectual Property Protection
Bettina Chen (EE)	Babak Parviz (EE)	Integration of Functional Electronic & Optoelectronic Devices on Contact Lenses
Omari Dennis (EE)	Eve Riskin (EE), Richard Ladner (CSE)	Mobile ASL
Louis Draghi (EE)	Babak Parviz (EE)	Experiments in Microscale Self-Assembly
Joseph Garrison (EE)	Sumit Roy (EE)	Wireless Test Beds & Cognitive Radio
Francisco Gomez Gamino (EE)	Gaetano Boriello (CSE)	Deciphering the Nike & iPod Sensor
Miguel Guzman (ME)	Scott Dunham (EE)	450mm Diameter Silicon Wafer Dynamics
Hannah Jimma (EE)	Karl Böhringer (EE)	Experiments in Microscale Self-Assembly
Nicholas LaVassar (EE)	Vikram Jandhyala (EE)	Computational Electromagnetics
Ahlmaz Negash (EE)	Karl Böhringer (EE)	Micro Electro Mechanical Systems
Brittany Redmond (EE)	Blake Hannaford (EE)	Haptic & Conversation Analysis
Michael Rush (EE)	Sumit Roy (EE)	Collaborative Networking
Kyle Sanchez (EE)	Brian Otis (EE)	Test & Characterization of Ultra-Low Power Circuitry
Anthony Seo (EE)	Anthony LaMarca (CSE)	Exploring the Feasibility of Machine Learning in Low-Power Embedded Systems
Sunny Sharma (EE)	Babak Parviz (EE)	Electronic Control of Apptides on Silicon Chips
Jessica Tran (EE)	Eve Riskin (EE)	Academic Tools for EE Education
Justin Tran (EE)	Wei-Chi Wang (ME)	Electro Rheological Fluid



EE undergraduate and EURP participant, Brittany Redmond demonstrating her project on Haptic and Conversation Analysis. See page 11 for more information about this project.

INTEL/UW RESEARCH

Intel supports a significant number of research projects annually in which EE Faculty and graduate students are partnering with Intel researchers and engineers. The faculty that have been involved in these projects include: David Allstot, Jeff Bilmes, Karl Böhringer, Scott Dunham, Vikram Jandhyala, Hui Liu, Alex Mamishev, Brian Otis, Eve Riskin, Sumit Roy, Jacques C. Rudell, Ming-Ting Sun, and Leung Tsang. The sponsored research areas include circuits, speech recognition, self assembly, semiconductor physics, wireless communications, sensors, RFIC, electromagnetics, signal integrity and photonics. Below are descriptions of just a few examples of what were done in these projects.

JEYANANDH PARAMESH (PH.D. '06), UW, AND DR. KRISHNAMURTHY SOUMYANATH, INTEL

Jeyanandh Paramesh, a graduate student in Professor Dave Allstot's Communication Circuits Lab, interned at Intel under the guidance of Dr. Krishnamurthy Soumyanath, who leads an RF/mixed-signal integrated circuits research group. The project designed fully-integrated multi-antenna transceivers for nanoscale CMOS technology. They successfully demonstrated the first fully integrated CMOS multi-antenna receiver and presented the research at the International Solid-State Conference in 2005. Soumyanath's mentoring included energetic questioning and staunch support for Paramesh's work on gaining silicon space. Paramesh was awarded the Intel Fellowship in 2003-2004, which allowed him to work at Intel on and off until the summer of 2005. Additional internships with Intel led to projects on a high-speed analog-to-digital converter to digitize Wi-Fi signals. Paramesh graduated from UW in 2006, and he is now an assistant professor of electrical and computer engineering at Carnegie Mellon University.

Soumyanath has been collaborating with Allstot's group for ten fruitful years that continues unabated. Their collaboration spans the entire spectrum from student internships through joint Ph.D. work and funded research, to hiring graduates for full-time positions at Intel. This partnership sets a very high bar for all future Intel/University engagements. The joint work has resulted in many seminal publications and awards along the way, the most recent of which is the Young Scientist Award for Ms. Parmoon Seddighrad (former Intel employee currently pursuing a Ph.D. at UW) from the ESSCIRC 2009 (European Solid State Circuits) Conference. The collaboration has seeded Carnegie Mellon University and Indian Institute of Science with young faculty.

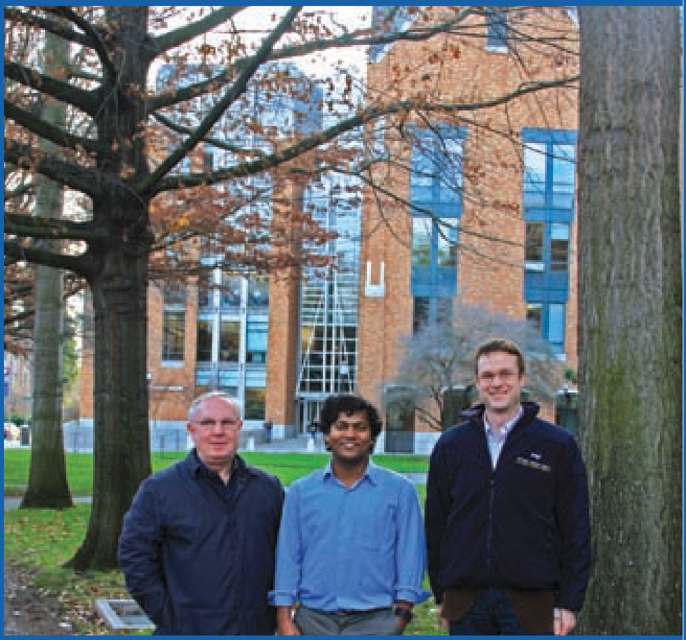
> “This partnership encourages an exchange of ideas and expertise resulting in innovative technologies at multiple locations. We couldn't be happier with our collaboration.”
>
> — KRISHNAMURTHY SOUMYANATH, INTEL

SUDIP SHEKHAR (PH.D. '08), UW, AND FRANK O'MAHONY, INTEL

Sudip Shekhar received the Intel Fellowship while pursuing a Ph.D. in EE and interned with the Circuit Research Lab at Intel, Hillsboro. The project focused on state-of-the-art wireline circuits for future generation I/O links.

"It was a remarkably valuable experience, to work and learn from a group of smart scientists and broaden my experience in the field of circuit design. The work place environment was ideal for a complete internship experience. I was mentored by the group members, especially Frank O'Mahony and Mozhgan Mansuri, and at the same time, given tremendous opportunities to work on challenging problems and contribute to two different projects."

— SUDIP SHEKHAR

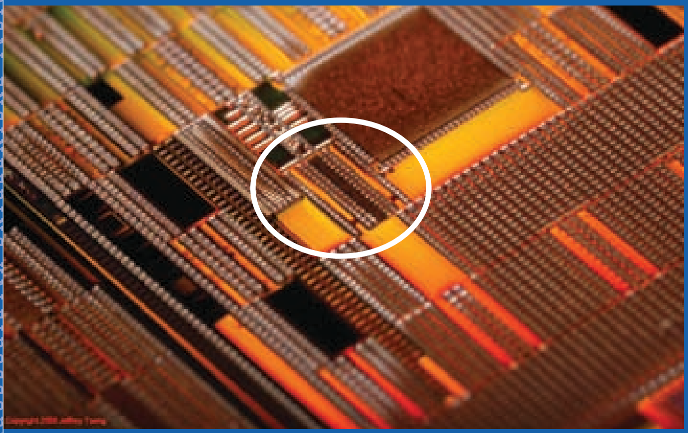


Professor Dave Allstot, Sudip Shekhar, and Frank O'Mahony.

A second internship provided experience in testing and measuring chip prototypes. Upon graduation, Shekhar joined the Circuit Research Lab as a research scientist. During Shekhar's internships he proved to be one of the top few interns the group has had over the past decade. Most notably, he worked on the design, analysis, and lab testing of a 27Gb/s serial link receiver prototype that served as the proof-of-concept for an injection-locked phase shifter. In addition, he developed fast-locking clock circuitry to enable fast power states for a low-power serial interface. This circuit was incorporated into a recent prototype that has demonstrated industry-best power efficiency.

"Considering the relatively short duration of internships, Sudip made remarkable contributions to the research efforts. Our research lab at Intel has benefited greatly from our relationship with the UW EE department."

– FRANK O'MAHONY



A 27Gb/s Forwarded-Clock I/O Receiver using an Injection-Locked LC-DCO in 45nm CMOS (ISSCC 2008, CICC 2008, TCAS 2009). Left: A wafer photo; Right: A wafer probe set-up. Frank O'Mahony, Sudip Shekhar, Mozhgan Mansuri, Ganesh Balamurugan, James E. Jaussi, Joseph Kennedy, Bryan Casper, David J. Allstot, Randy Mooney.

FUNLAB, UW, AND JING ZHU (Ph.D. '04) INTEL

Jing Zhu worked as a summer intern at Intel for 2003-2004, and became a full-time research scientist at the Communications Technology Lab after graduating from UW EE with Ph.D. in 2004. A significant part of Zhu's Ph.D. work ("Layer 2 (LL/MAC) performance analysis and improvement of wireless heterogeneous networks," supervised by Professor Sumit Roy) discovered the use of "physical carrier sensing" for improving network capacity of CSMA-based wireless networks, such as IEEE 802.11. This work could not have been done without close collaboration between UW EE and Intel. The basic concept was first identified and formulated when Zhu worked at Intel as an Intern. After completing the internship, Intel later funded the research project, "Adaptive Mesh" at UW EE to further investigate the concept. Upon joining Intel, Zhu continues to work with Professor Sumit Roy and other FUNLAB members as the project sponsor.

"As both a UW EE student and an Intel employee, I have benefited a lot from the close relationship between Intel and UW EE. The opportunity to work as an Intern at Intel is the direct outcome of such a relationship, and set me up for my career path at Intel. My training at UW EE provided a solid knowledge base in the wireless communications and networking area, strong research capabilities to identify, formulate, and solve new problems, and excellent analytical skills to evaluate and compare various solutions—all of which are very important for being successful as a researcher in the wireless industry."

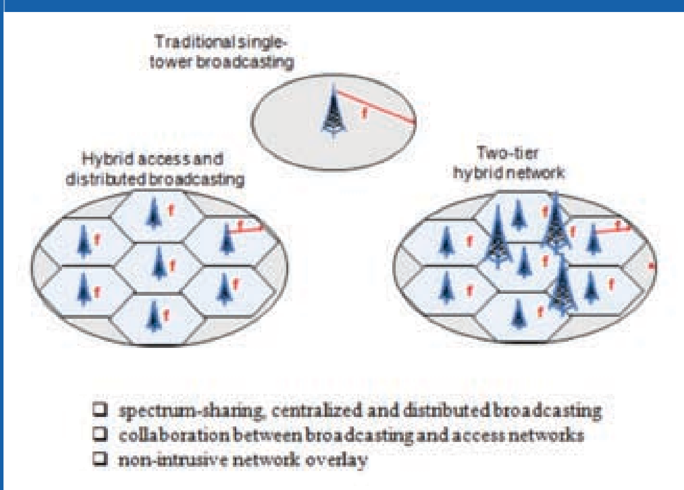
— JING ZHU

WIT LAB, UW, AND GUOQING LI (Ph.D. '04) INTEL

Over the last three years, Intel Research has sponsored the WIT lab at EE for research on "Wireless Hybrid Network," a project supervised by Professor Hui Liu. Guoqing Li worked with Professor Liu on developing new concepts, generating effective results and bringing those ideas back to Intel.

"With help from my advisor, my study in the department of EE was rewarding, not only in gaining a rigorous academic education, but also in understanding how to conduct research and how to explore innovative ideas, all of which have guided me throughout my work life at Intel Labs as a Research Scientist."

– GUOQING LI



Broadcast and Unicast Hybrid Network.

Broadcast TV uses a few, high power transmission towers; the transition to digital transmission will allow for higher spectral efficiencies due to single-frequency network (SFN). Nonetheless, one-way DTV broadcasting needs to improve coverage and lower transmission costs by transitioning to a set of more distributed, lower-power transmitters via gradual insertion of gap-filler or relay broadcast towers. A two-way cellular access network in the UHF band is ideally suited for point-to-point or point-to-multipoint wireless links (i.e. unicasting or multicasting). With the storage capability of user devices expanding at the rate of Moore's law, it only makes sense to take advantage of both networks to maximize the efficiency of content delivery. The Hybrid Network project aims to develop a coordinated video delivery strategy that pushes the common contents towards the end-devices through broadcasting networks and accommodates individual needs through cellular infrastructure.

INTEL LABS SEATTLE

At Intel Labs Seattle, Intel and UW researchers are exploring new technologies to support computing and communication environments and applications of the future. The lab is part of a novel experiment by Intel to accelerate long-term research by implementing an open collaborative model for industry–university research. Like its sister labs (Intel Labs Berkeley and Intel Labs Pittsburgh), Intel Labs Seattle has roughly 20 permanent staff plus an equal number of associated graduate and undergraduate students, interns, faculty and visitors. EE students and faculty are involved in interdisciplinary projects that encompass a range of topics from sensing and wireless systems, to machine learning and human-computer interaction, with an emphasis on system/sub-system level prototyping and their evaluation in real-world scenarios. More information about Intel Labs Seattle can be found at: www.seattle.intel-research.net/home.php

BRIAN OTIS, UW, AND JOSHUA SMITH, INTEL LABS SEATTLE

Assistant Professor Brian Otis is working with Josh Smith at Intel Labs Seattle to develop the Neural WISP (pictured below), a wireless neural interface operating from far-field radio-frequency RF energy. The group mapped the WISP RF front-end, protocol, amplifiers, ADC, and references to a single chip, allowing placement in applications that demand small form-factor. A demonstration of the project included flying the board on a moth while taking temperature readings from the insect. UW EE graduate students Dan Yeager, Helen Zhang, and Azin Zarrasvand were also involved in this project, and the chip was presented at the 2010 IEEE International Solid State Circuits Conference (ISSCC).

SUMIT ROY & VIKRAM JANDHYALA, UW, AND JOSHUA SMITH, INTEL LABS SEATTLE

Smith is currently a co-PI on an NSF Electrical, Communications & Cyber Systems Program entitled, "Realizing the Internet of Things via RFID Sensor Nets" with UW EE professors Sumit Roy and Vikram Jandhyala. The overall goals of the project, as suggested by the title, is to use novel RFID components—such as the Intel WISP—to develop a next-generation sensor network architecture. Specifically, the project seeks to exploit the emerging programmability of sensorized RFID tags such as WISP in conjunction with innovations to the RFID circuit, link and protocol layers to achieve enhanced link reliability, network throughput and power efficiencies.

JOSHUA SMITH is an Intel Principal Engineer and an affiliate faculty member in both the Electrical Engineering and Computer Science and Engineering departments. He leads projects on Personal Robotics, WREL (Wireless Resonant Energy Link), and WISP (Wireless Identification and Sensing Platform). As a doctoral candidate at the Massachusetts Institute of Technology, Smith invented an electric-field-based passenger airbag suppression system that is now standard equipment in all Honda cars. He obtained the Ph.D. and S.M. degrees from MIT, an M.A. in Physics from Cambridge University, and B.A. degrees in Computer Science and Philosophy from Williams College.

INTEL RESEARCHERS WORKING IN UW LABS

UW EE benefits from the exceptional opportunity to have Intel researchers working directly in the department labs. Their experience provides the research projects with "in-house" industry perspective, regular feedback, and student mentoring.

MEMS LABORATORY, UW, AND RAJASHREE BASKARAN, INTEL

Raji Baskaran was a researcher-in-residence/Affiliate Assistant Professor at UW from Intel from Fall 06-Summer 09. Baskaran had the opportunity to do focused work on a critical problem for the IC industry roadmap and was exposed to a multitude of research activities at UW. In particular, she worked with the MEMS Lab on two sub-projects (see EEK article on page 21 for more information about the Intel self-assembly project), working on self-assembly for meso-scale applications. She spent time doing both hands on lab experiments and advising the students on their work. Baskaran's exposure to the microfluidic droplet work in the MEMS Lab provided seeds for new concepts in self-assembly, which helped Intel see new ways of approaching the same problems.

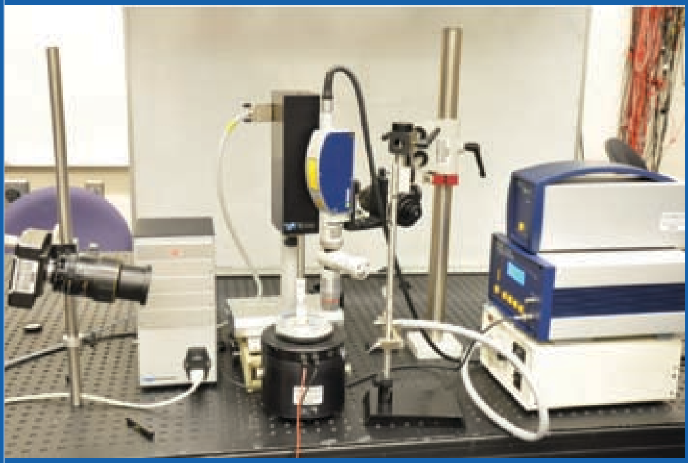
"We achieved significant milestones, showing 100% assembly in both the projects. The data that was collected and continues to be collected at UW are important for making technology decisions at Intel for future roadmap of processes."

– RAJI BASKARAN

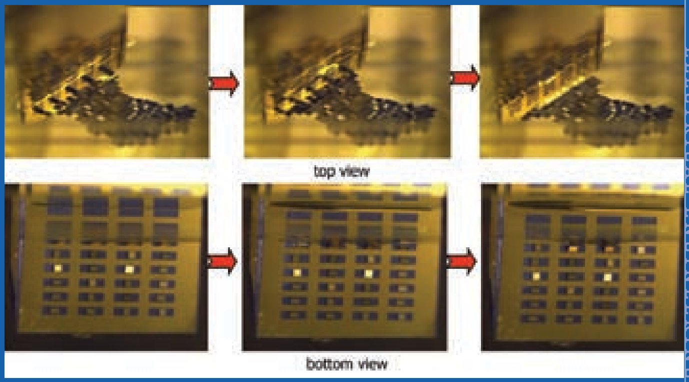
The student mentoring that Baskaran has provided also proves to be an invaluable asset to the students' research and educational experience. She has given several guest lectures in both core and special topic classes. Baskaran also co-organized a seminar series on 3D integrated challenges which provided a forum for productive and educational interactions with many other EE faculty from a wide range of research backgrounds.

"Raji really played a major role in my lab as researcher and mentor of graduate and undergraduate students, and continues to do so now. She is on the committees of several graduate students."

– PROFESSOR KARL BÖHRINGER



The experimental setup for fluidic self-assembly consists of a high-speed camera, linear electromagnetic vibration exciter, dip coater and laser vibrometer. Thin and fragile parts cannot be handled by pick-and-place robotics, so performing assembly in a fluidic medium is a viable method.



An example of a one-one-one part-to substrate assembly and self-centering from two immiscible liquid interfaces.

Automated Synthesis of High Speed Electronic Packages

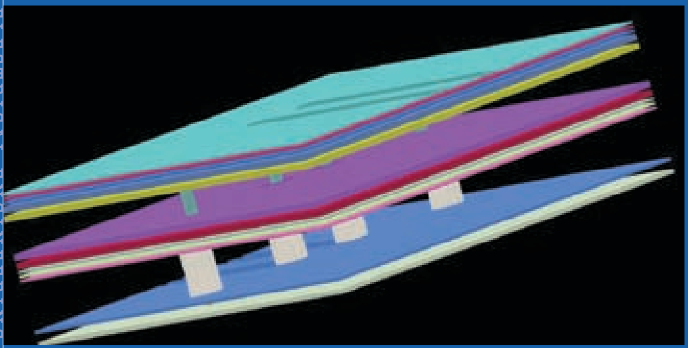
ARUN V. SATHANUR — Graduate Student (EE)

Today's world is surrounded by an astoundingly wide gamut of electronic systems. The integration of multiple functionalities demand higher data rates which in turn leads to higher frequencies of operation. Similar demands are observed across a broad range of electronic packaging technologies including system-on-chip and system-on-package architectures, targeting diverse market segments. It is therefore imperative that researchers develop and optimize the various feature dimensions of package interconnects to achieve designs with better bandwidth before attempting any structural changes. This work represents a small step towards the development of such an automated framework.

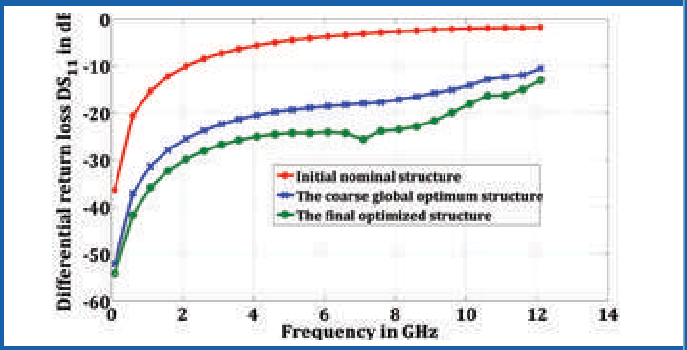
Researchers at UW EE's ACE Lab have developed a parametric model for a generic differential ten-layer microprocessor package line with two motherboard layers. Parametric analyses are carried out to assess the impact of various geometry parameters on the differential return loss of the interconnect which is directly related to the allowable data rate.

Even by using fast, full-wave EM solvers, the simulation of complex structures (such as the package vertical interconnect) takes a lot of computing time. An optimization approach with the EM solver in the loop is therefore challenging due to the EM solver needs and the high dimensionality of the optimization space.

To make the optimization problem tractable, flow is broken down into two distinct phases: a dimension reduction scheme, and a reusable, multi-dimensional look-up table. These two phases precede the global optimization phase which is facilitated by a smooth interpolation scheme based on splines. An accelerated boundary element based full-wave electromagnetic solver has been used to construct a look-up table of S-parameters for a number of designs. The second phase features a custom local optimizer that incorporates all the variables without any dimension reduction. This methodology has been applied to the automated synthesis of the differential package line resulting in a significant improvement in the return loss performance.



The profile view of the differential package line.



Frequency sweep comparison.

Future work will focus on optimizing the interconnect arrays and utilizing lookup tables in conjunction with the local optimizer for multi-objective optimization. Further, investigations into robust optimization under variability will be carried out. Effort will also extend this hierarchical approach to system level optimization by incorporating chip-side and board-level effects.

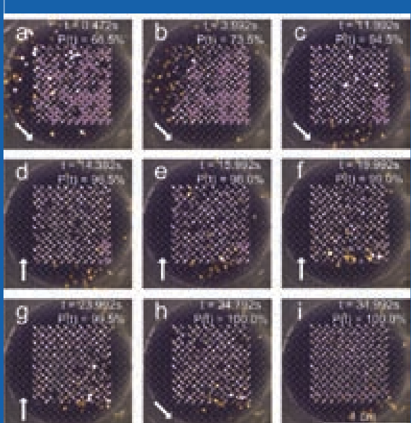
FACULTY ADVISOR: Vikram Jandhyala
RESEARCH AREA: Electromagnetics
GRANT/FUNDING SOURCE: Intel packaging SRS & the Intel Ph.D. Fellowship

Programmable Batch Assembly of Micro-components with 100% Yield

JI HOO — Graduate Student (EE)

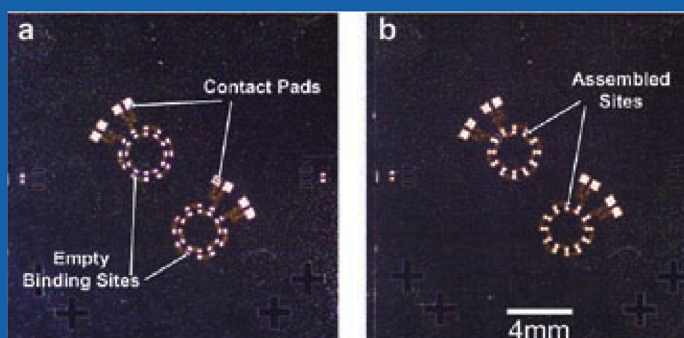
State-of-the-art electronics increasingly requires the integration of multiple functionalities often performed by fabricated micro-components using incompatible processes. As systems become more complex and the sizes of component devices continue to shrink, the use of pick-and-place robotics for system assembly is becoming more of a bottleneck to industrial throughput. Self-assembly is a strong candidate for performing system integration, especially at the micro-scale. Based on stochastic principles, researchers at the UWEE MEMS Laboratory have developed a template-based process for the assembly of silicon chips.

By identifying the behavior of micro-components when subjected to various frequencies, amplitudes, and tilt of a specially prepared vibrating platform, components can be induced to jump, vibrate in place, or move across a surface in a fashion that resembles walking. Using these controls, silicon chips can "walk" across an assembly template, and then drop/assemble into designated apertures. Assembled components will remain within the apertures because only the stimulus to "walk" is supplied, but that does not allow any chip to jump out from the apertures. Using an optical feedback mechanism, vacant apertures are registered and then free components are directed to them to ensure 100% assembly. When the assembly process is complete, a walking mode can also be used to move all excess parts away from the assembly area.



Various stages of a feedback driven assembly: **a** shows an instance of switching from jumping mode (with a top-left corner bias) to walking mode with part-motion direction indicated by the white arrow in the box. **b** and **c** show the progressive filling of the entire assembly area. Right after **c**, when assembly-percentage, **P(t)** plateaus, a walking mode is activated in the upwards direction as seen in **d**, **e**, **f**, and **g**, moving excess parts below the assembly area to the empty sites. After achieving 100% assembly in **h**, a walking mode is employed towards the lower-right corner, moving excess parts away from the assembly area, and thereby finishing the process in **i**. (note: size-scale provided in image **i**).

Besides silicon chips, this template-based assembly method can also be applied to the assembly and mounting of surface mount technology (SMT) passive components of the 01005 format (0.016"×0.008", 0.4mm×0.2mm). Preliminary results are promising; SMT components have been successfully mounted at arbitrary orientations on the mounting surface (another bottleneck of pick-and-place robotics), and electrical connectivity of the solder bonds have been verified.



Assembly of SMT components at arbitrary orientations: **a** shows a test-circuit fabricated on a silicon substrate. **b** shows the same test-circuit completed with the assembly of 01005 capacitors.

With further refinement of the assembly processes, these advancements in the field of heterogeneous integration will greatly improve the throughput and packing densities of integrated devices, thereby enabling many novel innovations.

FACULTY ADVISOR: Karl F. Böhringer
COLLABORATORS: Affiliate Assistant Professor Rajashree Baskaran, Xiaorong Xiong (Intel Corporation)
RESEARCH AREA: Self-assembly
GRANT/FUNDING SOURCE: DARPA, Intel Corporation

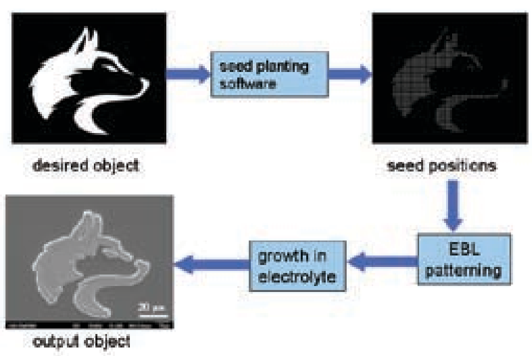
Optimal Seed Planting
for Growth-Regulated Nanomanufacturing

SHAGHAYEGH ABBASI — Graduate Student (EE)

Nanotechnology has become increasingly important due to its expected high impact on health, environment, energy, and many other aspects. In electronics, nanotechnology can be used to increase the density of components, decrease the cost, and increase the performance per device and per integrated circuit.

The key attributes in any nanomanufacturing process consist of cost, flexibility, quality, time, and precision. This research offers a fully automated method for manufacturing micro and nano structures to reduce cost and process time compared to conventional serial manufacturing methods without threatening the attributes of flexibility and quality. In addition, methods for optimizing the structure precision are also proposed.

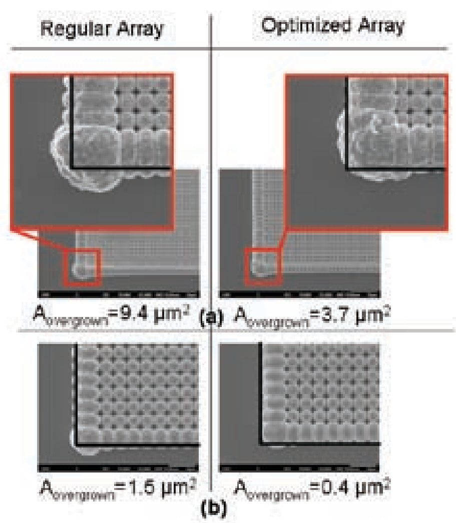
Pattern creation is usually the most expensive step in nanomanufacturing since it often relies on serial rate tools (e.g. e-beam and dip-pen lithography). However, planting growth-initiating "seeds" only at selected locations (just a fraction of total object area) can be used for patterning, making it faster and cheaper. This project develops an automated method which takes a geometric representation of an object as the input, produces the seed positions for entry to fabrication tools, and gives the grown object as the output. To improve the structure precision, a model for seed-initiated material growth is first developed based on



The automated process: the desired object is the input, and the grown object is the output.

Green's function calculations. This model is then used to develop an algorithm for optimal seed planting to produce the highest accuracy object with the fewest number of tool moves.

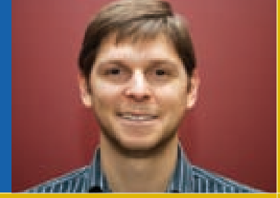
In current experiments, copper electroplating seeds are patterned for gold growth using electron beam lithography (EBL). The growing radius of a single seed is calculated using mass flow equilibrium. For seeds growing in an array, the metal ion concentration around each seed is affected by the neighbor seeds. This effect has been modeled here for the first time using the Green's function solution of diffusion equation, and the model is supported by experimental results. The model is then used to optimize the seed positioning to significantly improve the structure precision according to experimental results.



The regular square array (left) and the optimized array (right) are shown for (a) 250 nm seeds with 1.5 μm spacing and 12 seconds growth time, and (b) 500 nm seeds with 10 μm spacing and 60 seconds growth time. The optimized seeds show a sharper corner and a smaller overgrown area.

The growth-regulated nanomanufacturing method reduces the cost and process time significantly compared to conventional serial methods. It is also flexible since the desired structure can be entered in the computer software, hence no hardware change is needed for different structures. This method has the potential to be used for fabrication of multi-material systems and 3-D structures.

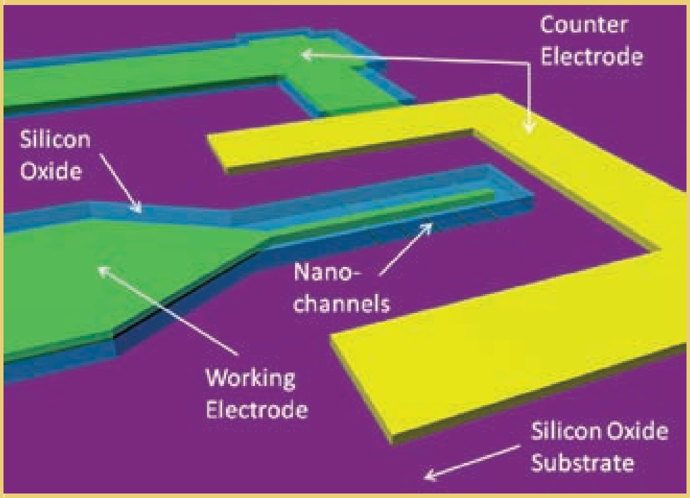
FACULTY ADVISORS: Karl F. Böhringer (EE) & Daniel T. Schwartz (ChemE)
COLLABORATORS: Sathana Kitayaporn, Graduate Student (ChemE)
RESEARCH AREA: MEMS & Manufacturing
GRANT/FUNDING SOURCE: National Science Foundation Grant CMMI 0709131 "NIRT: Protein-guided Nanomanufacturing"



Electronic Detection of Biomolecules Using Nanofluidic Channel Sensors

ANDREI AFANASIEV — Graduate Student (EE)

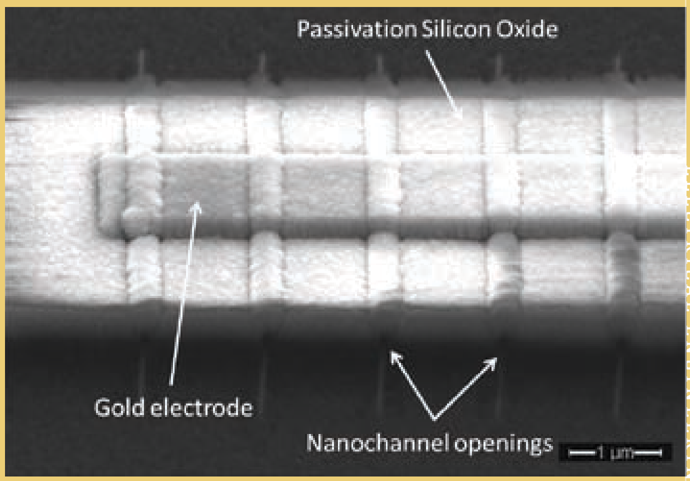
Studying the behavior of individual living cells is one of the most exciting topics in microbiology research today. Characterizing the functionality of a single cell involves accurately monitoring the transit of biomolecules across the cell's membrane. However, the lack of a precise and convenient method for monitoring very small concentrations of such biomolecules is an essential technological limitation. This research aims to develop a novel, nanoscale biomolecule sensor that precisely and non-intrusively measures minute concentrations of various molecules essential to cell biology, thus enabling an entirely new direction of microbiology research.



A 3D model of the nanoscale channel biomolecular sensor.

Current gold standard in biomolecular detection labels target molecules with fluorescent dyes to study the sample using an elaborate laser microscope. However, this method is not effective for studying single cells because the dye used to mark the molecules can interfere with cell function. Subjecting the cells to the stresses of a high powered laser microscope can also unpredictably change the cell's behavior. The sensor in this research relies on a purely electronic readout which does not require introduction of dyes or invasive imaging techniques.

These sensors have been fabricated to consist of nanoscale "tunnels" microfabricated in a layer of silicon oxide with gold microelectrodes placed both inside and outside of these tunnels. By submerging the sensor into a liquid and applying a voltage to the electrodes, electrical conductivity can be measured through the liquid filling the tunnels. Specific biomolecule receptors are attached to the inside walls of the tunnels so that if the receptor's target molecule is present in the solution, it will be immobilized inside the tunnel. The cross-section of the tunnels is comparable in size to that of the target molecules; an immobilized molecule will significantly constrict the tunnel which can be sensed by observing a drop in the read-out current.



A Scanning Electron Microscope image of the nanochannel sensor.

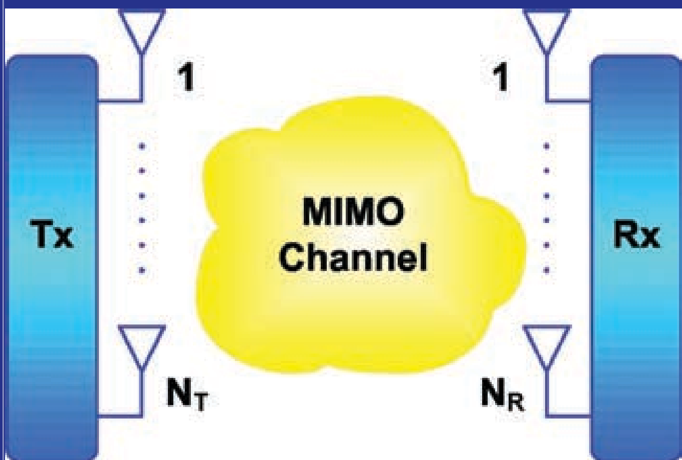
An array of such sensors will offer simultaneous multi-molecule sensing capability which will allow biologists to study the characteristics of a single living cell. Understanding the mechanisms behind cell function opens doors to new treatments and diagnosis methods of diseases such as cancer and various immune system disorders.

FACULTY ADVISOR: Babak Parviz
COLLABORATORS: Professor Brad Cookson (UW Med), Dr. Brian Reed (Fred Hutchinson Cancer Research Center), Microscale Life Sciences Center
RESEARCH AREA: MEMS
GRANT/FUNDING SOURCE: National Institutes of Health

Optimal Training Length for MIMO ISI Channels with Time-Variation

XIANG ZOU — Graduate Student (EE)

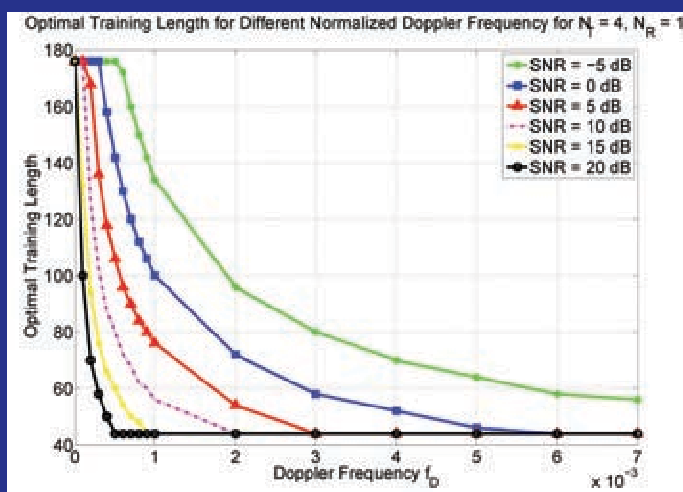
Rapidly fading channels are usually encountered in many mobile communication systems, for example, under water acoustic channel interfered by surface scattering and internal waves, and motor vehicle network with objects moving around. Most sophisticated communication systems today employ multiple antennae to increase the data transmission rate. In this research, the multiple-input and multiple-output (MIMO) channel estimation performance is investigated under the time-varying effect using a special kind of orthogonal sequence.



A MIMO communication system.

Accurate channel state information estimation plays an important role in taking advantage of the MIMO potential capacity in many communication systems. Compared to the blind estimation, the training-based channel estimation is more prevalent for its simple implementation and better performance. The transmitters first send some symbols known to the receiver before the data. Then, the receiver will estimate the channel information based on the received signal corresponding to the training symbols which subsequently decodes the data using the estimated channel state information.

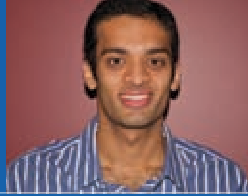
In order to use the bandwidth more efficiently, the zero correlation zone sequences are used because they are easier to implement and more robust against channel time-variation. Previous work only considered the flat fading channel case, which cannot fully describe channels with long delay spread, and it gave little consideration to the training sequence used. This work has shown that the overall estimation mean square error (MSE) is comprised of two parts; the error due to noise decreases as sequence length increases, and the error due to time-varying increases as training sequence length increases. For the case when minimum training length is used, the computation of MSE due to channel temporal fluctuation can be further simplified and is only dependent on the channel characteristics. Moreover, for a given type of training sequence, the optimal training length is a function of normalized Doppler frequency and the signal-to-noise ratio.

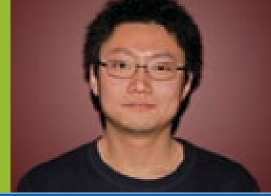


The optimal training length for a MIMO system at different operating scenarios with four transmitters and 10-tap channel.

Based on these results, future work will investigate the sequence design for more general channel models and sparse-channel estimation.

FACULTY ADVISOR: James A. Ritcey
RESEARCH AREA: Wireless Communication
GRANT/FUNDING SOURCE: the Office of Naval Research Grant N00014-07-1-0600, & the Army Research Office Grant MURI W911NF-07-0287





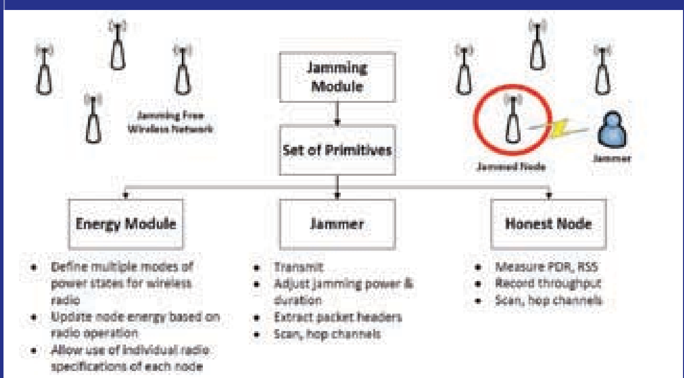
Modeling Jamming Attacks & Mitigation in Wireless Networks

SIDHARTH NABAR & HE WU — Graduate Students (EE)

Jamming is an important example of Information Warfare/Electronic Warfare (IW/EW) attacks in wireless networks. It is easy to mount and highly effective in disrupting network performance or data throughput. A jamming attack comprises of a malicious node that deliberately transmits a signal to interfere with an honest sender's data transmission. Currently, there are several simulation/emulation toolkits available for wireless networking research such as the Boeing CORE, ns-3 and OPNET. However, there are no generic tools to model IW/EW attacks and their mitigation. Researchers from UW EE's Network Security Lab are creating a software module to effectively model jamming attacks and study their effects on wireless networks through simulation/emulation.

The module designed in this project has been implemented in the ns-3 network simulator, which is an open source network research toolkit. This module includes three sets of primitives (Energy Model, Jammer, and Honest Node) which act as building blocks for implementing different types of jamming attacks, their detection and mitigation in WiFi networks.

This module, when combined with the ns-3 network simulator, will enable wireless network researchers to easily simulate various jamming strategies and mitigation techniques and verify theoretical results. A demonstration of such a simulation was given as a proof of concept, and successfully showed the efficacy of the designed module.

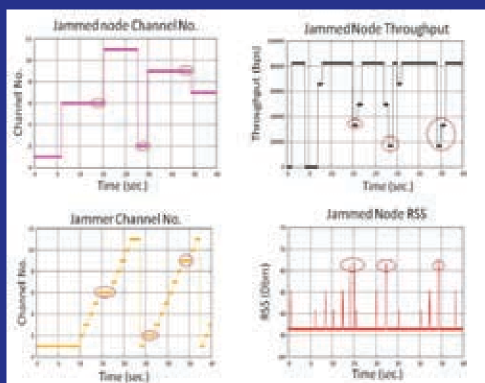


The three primitives defined for the jamming module. The provided primitives are:

1. Energy Model: Energy consumption is a significant metric in several wireless network strategies, the module provides a set of primitives for the network nodes and jammers to have energy update capabilities.

2. Jammer: The primitives in this part are defined for the jammer node, and include basic functions that enable the jammer to perform different types of jamming attacks.

3. Honest Node: This part contains primitives which give the network nodes extra capabilities (in addition to normal wireless operation) that can be used to detect the jamming attack and defend against it.



Simulation results showing jamming attack, jamming attack detection and jamming attack mitigation. When jammer is in the same channel as the honest nodes, a fluctuation of network throughput is observed. Once jamming attack is detected, the honest nodes hop to a different channel to avoid the attack. The jammer also reacts to honest nodes' mitigation by scanning all channels for signal and jam on a new channel.

The current module can effectively model several types of jamming attacks and some basic mitigation techniques. It will be further extended to cover more advanced jamming attacks and mitigation techniques such as DSSS and FHSS. The integrations of the module with larger simulation toolkits will also be pursued in order to make it more usable for the research community.

FACULTY ADVISOR: Radha Poovendran
COLLABORATORS: Dr. Jae Kim, Dr. Danilov Claudio, Dr. Thomas Henderson & Mr. Jeffrey Ahrenholz (Boeing)
RESEARCH AREA: Wireless Networks
GRANT/FUNDING SOURCE: Boeing Company, US Army Research Office

ee

Faculty

AFROMOWITZ, MARTY
Professor
Microtechnology/Sensors
Ph.D., 1969 Columbia University
NIH Career Development Award

ALLSTOT, DAVID
Professor
System-on-Chip VLSI
Ph.D., 1979 UC-Berkeley
IEEE Fellow

ANANTRAM, M.P.
Professor
Nanotechnology, Materials & Devices
Ph.D., 1995 Purdue University

ARABSHAHI, PAYMAN
Assistant Professor WOT
Signal Processing & Communications
Ph.D., 1994 University of Washington

ATLAS, LES
Professor
Signal & Image Processing
Ph.D., 1984 Stanford University
NSF Presidential Young Investigator
IEEE Fellow

BILMES, JEFF
Associate Professor
Signal & Image Processing
Ph.D., 1999 UC-Berkeley
NSF CAREER Award

BÖHRINGER, KARL
Professor
Microelectromechanical Systems (MEMS)
Ph.D., 1997 Cornell University
NSF CAREER Award

BUSHNELL, LINDA
Research Assistant Professor
Controls & Robotics
Ph.D., 1994 UC-Berkeley
NSF ADVANCE Fellow

CHIZECK, HOWARD
Professor
Controls & Robotics
Sc.D., 1982 MIT
IEEE Fellow

CHRISTIE, RICH
Associate Professor
Energy Systems
Ph.D., 1989 Carnegie Mellon University
NSF Presidential Young Investigator

CRUM, LAWRENCE
Research Professor
Medical Ultrasound
Ph.D., 1967 Ohio University
ASA Fellow

DAILEY, DANIEL J.
Research Professor
Intelligent Transportation Systems
Ph.D., 1988 University of Washington

DARLING, R. BRUCE
Professor
Devices, Circuits, & Sensors
Ph.D., 1985 Georgia Institute of Technology

DUNHAM, SCOTT
Professor
Materials & Devices
Ph.D., 1985 Stanford University

EL-SHARKAWI, MOHAMED
Professor
Intelligent Systems & Energy
Ph.D., 1980 University of British Columbia
IEEE Fellow

FAZEL, MARYAM
Assistant Professor
Control & Optimization, Systems Biology
Ph.D., 2002 Stanford University
NSF CAREER Award

GUPTA, MAYA
Associate Professor
Signal Processing
Ph.D., 2003 Stanford University
ONR YIP Award, PECASE Award

HANNAFORD, BLAKE
Professor
Biorobotics
Ph.D., 1985 UC-Berkeley
NSF Presidential Young Investigator, IEEE EMBS Early Career Achievement Award, IEEE Fellow

HAUCK, SCOTT
Professor
VLSI & Digital Systems
Ph.D., 1995 University of Washington
NSF CAREER Award, Sloan Research Fellowship

HOCHBERG, MICHAEL
Assistant Professor
Nanophotonics
Ph.D., 2006 California Institute of Technology
AFOSR YIP Award, PECASE Award

HWANG, JENQ-NENG
Professor
Signal & Image Processing
Ph.D., 1988 University of Southern California
IEEE Fellow

JANDHYALA, VIKRAM
Associate Professor
Electromagnetics, Fast Algorithms, Devices
Ph.D., 1998 University of Illinois
NSF CAREER Award

JARUWATANADILOK, SERMSAK
Research Assistant Professor
Electromagnetics
Ph.D., 2003 University of Washington

KIM, YONGMIN
Professor
Digital Systems, Image Processing & Medical Imaging
Ph.D., 1982 University of Wisconsin - Madison
IEEE Fellow, IEEE/EMBS Early Career Achievement Award

KIRCHHOFF, KATRIN
Research Associate Professor
Multilingual Speech Processing, Machine Learning
Ph.D., 1999 University of Bielefeld

KLAVINS, ERIC
Associate Professor
Controls & Robotics
Ph.D., 2001 University of Michigan
NSF CAREER Award

KUGA, YASUO
Professor
Electromagnetics
Ph.D., 1983 University of Washington
NSF Presidential Young Investigator Award, IEEE Fellow

LIN, LIH
Professor
Photonics, MEMS
Ph.D., 1996 UC-Los Angeles
IEEE Fellow

LIU, HUI
Professor
Communications & Signal Processing
Ph.D., 1985 University of Texas, Austin
NSF CAREER Award, ONR Young Investigator Award, IEEE Fellow

MAMISHEV, ALEX
Associate Professor
Electric Power Systems, MEMS, Sensors
Ph.D., 1999 MIT
NSF CAREER Award

NELSON, BRIAN
Research Associate Professor
Plasma Physics
Ph.D., 1987 University of Wisconsin - Madison

OSTENDORF, MARI
Professor & Associate Dean of Research
Signal & Image Processing
Ph.D., 1985 Stanford University
IEEE Fellow

OTIS, BRIAN
Assistant Professor
RF/Analog IC Design
Ph.D., 2005 UC-Berkeley
NSF CAREER Award

PARVIZ, BABAK
Associate Professor
Microelectromechanical Systems (MEMS)
Ph.D., 2001 University of Michigan
NSF CAREER Award

PATEL, SHWETAK
Assistant Professor
Ubiquitous Computing, Sensors, Embedded Systems
Ph.D., 2008 Georgia Institute of Technology

PECKOL, JAMES K.
Senior Lecturer
Ph.D., 1985 University of Washington

POOVENDRAN, RADHA
Associate Professor
Communications Networks & Security
Ph.D., 1999 University of Maryland
NSA Rising Star Award, NSF CAREER Award, ARO YIP and ONR YIP Awards, PECASE Award

RISKIN, EVE
Professor & Associate Dean
Signal & Image Processing
Ph.D., 1990 Stanford University
NSF Presidential Young Investigator, Sloan Research Fellowship, IEEE Fellow

RITCEY, JAMES A.
Professor & Associate Chair for Education
Communications & Signal Processing
Ph.D., 1985 UC - San Diego

ROY, SUMIT
Professor & Associate Chair for Research & Development
Communications & Networking
Ph.D., 1988 UC - Santa Barbara
IEEE Fellow

RUDELL, JACQUES C.
Assistant Professor
RF Integrated Circuits
Ph.D., 2000 UC-Berkeley

SAHR, JOHN
Professor & Associate Dean for UGrad Academic Affairs
Electromagnetics & Remote Sensing
Ph.D., 1990 Cornell University
NSF Presidential Young Investigator, URSI Booker Fellow, URSI Young Scientist Award

SEELIG, GEORG
Assistant Professor
Biological Circuits
Ph.D., 2003 University of Geneva
NSF CAREER Award

SHAPIRO, LINDA
Professor
Signal & Image Processing
Ph.D., 1974 University of Iowa
IEEE Fellow, IAPR Fellow

SHI, C.J. RICHARD
Professor
VLSI & Digital Systems
Ph.D., 1994 University of Waterloo
NSF CAREER Award, IEEE Fellow

SOMA, MANI
Professor & Associate Vice Provost for Research
Mixed Analog-Digital System Testing
Ph.D., 1980 Stanford University
IEEE Fellow

SUN, MING-TING
Professor
Signal & Image Processing
Ph.D., 1985 UC-Los Angeles
IEEE Fellow

TSANG, LEUNG
Professor & Chair
Electromagnetics, Remote Sensing
Ph.D., 1976 MIT
IEEE Fellow, OSA Fellow

WILSON, DENISE
Associate Professor
Circuits & Sensors
Ph.D., 1995 Georgia Institute of Technology
NSF CAREER Award

EMERITI

ALBRECHT, ROBERT
Controls & Robotics
Ph.D., 1961 University of Michigan

ALEXANDRO, FRANK
Controls & Robotics
Ph.D., 1961 University of Michigan

ANDERSEN, JONNY
Circuits & Sensors
Ph.D., 1965 MIT

BJORKSTAM, JOHN L.
Controls & Robotics
Ph.D., 1958 University of Washington

DAMBORG, MARK
Energy Systems
Ph.D., 1969 University of Michigan

DOW, DANIEL G.
Ph.D., 1958 Stanford University

GUILFORD, EDWARD C.
Ph.D., 1960 UC-Berkeley

HARALICK, ROBERT
Signal & Image Processing
Ph.D., 1969 University of Kansas
IEEE Fellow

HELMS, WARD
Circuits & Sensors
Ph.D., 1968 University of Washington

ISHIMARU, AKIRA
Electromagnetics & Waves in Random Media
Ph.D., 1958 University of Washington
IEEE Fellow, OSA Fellow, IOP Fellow, IEEE Heinrich Hertz Medal, URSI John Dillinger Medal and Member, National Academy of Engineering

JACKSON, DARRELL
Ph.D., 1977 California Institute of Technology

JOHNSON, DAVID L.
Ph.D., 1955 Purdue University

LAURITZEN, PETER O.
Ph.D., 1961 Stanford University

MORITZ, WILLIAM E.
Ph.D., 1969 Stanford University

PEDEN, IRENE
Ph.D., 1962 Stanford University
NSF "Engineer of the Year" Member, National Academy of Engineering, IEEE Fellow, IEEE Harden Pratt Award, U.S. Army Outstanding Civilian Service Medal

PORTER, ROBERT B.
Ph.D., 1970 Northeastern University
ASA Fellow, OSA Fellow

POTTER, WILLIAM
MSEE, 1959 US Naval Postgraduate School

SIGELMANN, RUBENS A.
Ph.D., 1963 University of Washington

SPINDEL, ROBERT
Signal Processing/Ocean Acoustics
Ph.D., 1971 Yale University
IEEE Fellow, ASA Fellow, MTS Fellow, A.B. Wood Medal, IEEE Oceanic Engineering Society Technical Achievement Award

YEE, SINCLAIR
Photonics, Sensors
Ph.D., 1965 UC – Berkeley
IEEE Fellow

ZICK, GREG
VLSI & Digital Systems
Ph.D., 1974 University of Michigan

Congratulations to Maya Gupta and Eric Klavins who were promoted to Associate Professors, and to Lih Lin who was promoted to Full Professor.

We apologize for any errors, omissions or misspellings in 2010 EEK. We would like to extend special appreciation to the faculty, staff and students who assisted in producing this publication and to the sponsors whose generosity made it possible.

Professional Masters Program

The Professional Masters Program (PMP) in Electrical Engineering serves the growing need for engineers and scientists in the Puget Sound region to earn an advanced degree. It offers an exceptional course structure for professionals seeking to expand their career opportunities in the field of electrical engineering. Launched in early 2008, the PMP is celebrating its first cohort of graduates this academic year. Students in the program represent a breadth of companies from the region including Agilent, Avtech, Boeing, Cypress Semiconductor, Fluke, Intel, Intermec, Kimberly-Clark, Microsoft, Motorola, Panasonic Avionics, and T-Mobile, to name but a few.

With a stellar curriculum equivalent to the daytime masters program, the PMP offers a wide range of courses, from wireless communications and electromagnetics to microelectromechanical systems. Courses are taught by UW EE faculty members, and are scheduled in the evening so that students generally come to campus only once per week.

The PMP leads to the same degree (MSEE) offered through the daytime program, and it is designed to allow students to complete requirements on a part-time basis over three years. Options exist for students to make faster progress through the program, should they so desire.

The EE department is currently launching a new set of PMP courses in Smart Grid Technologies and Management. This 3-course set is also available as a Certificate option for non-degree-seeking individuals. In addition to the Smart Grid Technologies and Management Certificate, the department has further plans to develop Certificate programs in Electromagnetics, Wireless Communications, and Signal Processing.

To learn more about the PMP and the department's new Certificate programs, please visit www.ee.washington.edu/academic/pmp, or email the PMP Advisor at eepmp@u.washington.edu.

Industrial Connections Program

The EE Department is excited to announce the launch of our new Industrial Connections Program (ICP). The ICP provides member companies access to a collaborative environment in relation to electrical engineering research, development, and employment of our students and alumni. Among the direct benefits to ICP members is attendance at an annual event highlighting EE faculty/student research, as well as a recruitment fair to attract our top students.

To learn more about becoming a member of the ICP contact the Associate Chair for Research and Development at chair_res@ee.washington.edu.

Distinguished Achievement in Industry — Richard Citta

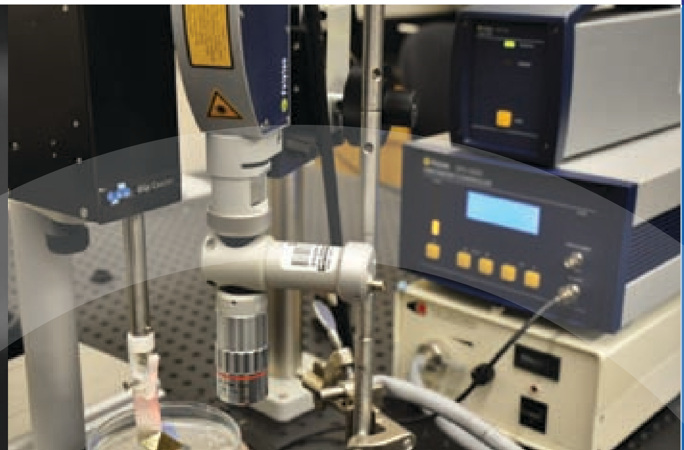
'71 MS, Electrical Engineering

The transition from the 70-year-old analog NTSC system to digital high-definition transmission has forever changed television broadcasting, and this "clear vision" was brought to millions of living rooms across the country by UW EE alumnus, Richard Citta. On May 7th, 2010, Citta will be honored for his distinguished achievement in industry with the UW College of Engineering Diamond Award.

Over his long career as a research engineer at Zenith Electronics, Citta played a critical role in pioneering HDTV. Led by Citta, Zenith pioneered the adoption of 8-level vestigial side-band (8-VSB) transmission scheme that is now the North American digital standard. 8-VSB's lack of interference with analog channels allowed the Federal Communications Commission to implement a 10-year transition. Since 1999, US consumers have bought more than 200 million HDTV sets. The energy efficiency of VSB transmission also has significantly reduced energy consumption and freed up spectrum for new wireless services and enhanced public security.

Colleagues describe Citta as exemplifying "the best in the engineering field" and a true educator and mentor who encouraged his team to think outside the box. He holds more than 100 patents and has received numerous honors for his work, including Zenith's Robert Adler Technical Excellence Award and the IEEE 2006 Masaru Ibuka Consumer Electronics Award. In 1997 his team received an Engineering Emmy from the Academy of Television Arts and Sciences. Citta is now a private consultant working on concepts to advance digital TV for use in rapidly moving vehicles and small handheld devices.

UNIVERSITY OF WASHINGTON
DEPARTMENT OF ELECTRICAL ENGINEERING
PAUL ALLEN CENTER — ROOM AE100R
CAMPUS BOX 352500
SEATTLE, WASHINGTON 98195-2500



www.ee.washington.edu

eeK
[Annual Research Review]