Cleveland State University
engaged learning

FENN RESEARCH

Fenn College of Engineering

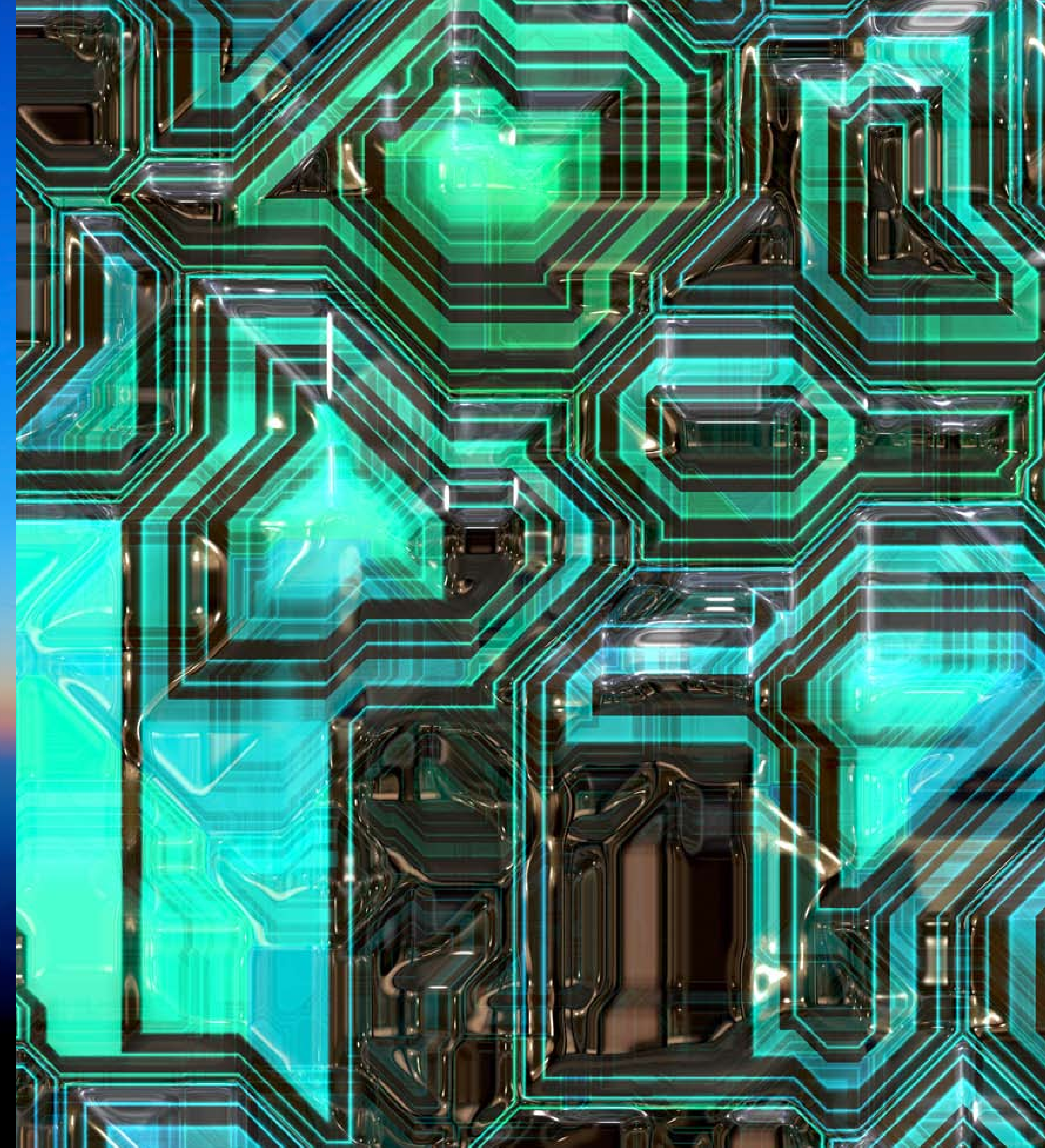
Cleveland State University

MESSAGE FROM THE DEAN

I hope you enjoy reading this first edition of our *Fenn Research* magazine. The Fenn College of Engineering at Cleveland State University has a long history of academic excellence with a strong liaison with industry. Since 1923, Fenn College has provided a tradition of high-quality undergraduate and graduate education in engineering. Basic and applied research is central to the mission of the college, as you will observe in the following pages. Our faculty members are nationally and internationally renowned for their research expertise and accomplishments, attracting external funding from local, state and national agencies, foundations and industry. They have received prestigious awards, such as NSF Career Award, Fulbright Awards and endowments, and have been recognized by their peers on the national level as many have become Fellows of their professional societies and editors of prestigious journals. Research and scholarly activities have continued with greater noticeable success as a Fenn College faculty recently became a member of a U.S. team that placed an experiment on the International Space Station. The results of the cutting-edge research of our faculty in areas such as biomedical engineering, materials science, renewable and sustainable energy, transportation safety and dynamics and control have been published in the most prestigious high-impact-factor scientific journals and have been continuously covered by local and national media. Assisted by our outstanding students, faculty have built a strong reputation for cutting-edge research in state-of-the-art laboratories. Funding from major corporate sponsors (Parker Hannifin, Rockwell Automation, Siemens and the Cleveland Clinic), federal agencies (the National Aeronautics and Space Administration, the National Science Foundation, the Department of Defense, the Department of Energy and the Department of Transportation), the State of Ohio and national associations and foundations (the American Diabetes Association and the American Heart Association) helps us become key participants in contributing to the rapid technological changes that lead to regional and national economic development and enables our students to network with leaders in their fields.

I recently pointed out in my 2010 State of the College Address (http://www.csuohio.edu/engineering/aboutfenn/stateoffenn.html) and I would like to repeat in this publication that we are in an age that not many significant achievements can take shape in isolation. Interdisciplinary collaboration is in fact a necessity in taking an idea from its theoretical and formative stage to a practical level. Let me share with you a fascinating story from one of our outstanding researchers whose experimental sample was recently taken to the International Space Station for further experimentation. He wrote to me regarding the difficult journey that his experimental sample travelled: "After being grown at CSU, [the sample travelled] to France for machining and integration, [then] to European Space Agency (Germany) for further integration with thermocouples and sealing into one of ESA Sample Cartridge Assembly (SCA), [then travelled] back to Houston for pay-load integration (as part of ESA-Low gradient Furnace and the NASA-Materials Science Research Rack), and then [went] to the Kennedy Space Center for launch by Discovery to the International Space Station only to be re-melted and directionally solidified in low gravity, [it was then] brought back to [earth to] the Kennedy Space Center by [Shuttle] Endeavour, [and was] taken to Marshall Space Flight center (Huntsville) for decoupling the sample from the SCA, and finally brought back to CSU."

Another example of collaboration is our newly established Center for STEMM Education which will bring together the expertise among three CSU colleges, namely: Engineering, Science and Education. This new



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center will serve as a coordinating body to encourage innovative Science, Technology, Engineering, Mathematics and Medicine education programs, strengthen community partnerships and the K-12 student pipeline, increase grant activity and support promising programs related to STEMM.

In the area of Relations with Industry, we continued to build a solid foundation for the newly formed Fenn Research & Development Institute (FRDI) by receiving university approval for a set of policies jointly developed by engineering faculty, University Office of General Counsel and Office of Sponsored Research Programs in order to facilitate the interactions among the faculty members and local industry. Moreover, we recently established the Center for Advancements in Renewable Energy. I look forward to the Center's accomplishments under the supervision of our newest endowed chair.

Our co-operative education (co-op) program is the first US program to be accredited by the Canadian Association For Co-operative Education (CAFCE). Our co-op students have been performing their internships in organizations such as NASA, the Ohio Department of Transportation, and in companies such as Parker Hannifin, Rockwell Automation, GE Lighting, Middough, Keithley, Ford, Lincoln Electric, Sherwin Williams, FirstEnergy, Lubrizol, and many more.

The expertise of our faculty combined with invaluable input from our industry advisory committees have kept our emphasis high on developing contemporary course curricula which are constantly being upgraded to follow current scientific trends. We are also dedicating our effort to developing more study abroad programs (including international co-op internships) as well as increasing the number of distance-learning courses. I invite you to read the following pages and enjoy this inaugural edition of *Fenn Research*. Please visit our web site at http://www.csuohio.edu/engineering to learn more.

BAHMAN GHORASHI, Ph.D.
DEAN, FENN COLLEGE OF ENGINEERING

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Selected External Funding

The Fenn College of Engineering has been very successful in receiving funding from local, State, and national agencies, industry, and other sponsors and donors. The following is a sample list of some of the most recent active grants and endowments.

$1,712,184
U.S. Department of Transportation
Department of Civil and Environmental Engineering
Project: University Transportation Center for Work Zone Safety and Efficiency

$530,000
U.S. Army Power Division (through General Technical Services)
Department of Mechanical Engineering
Project: Production of High Conductivity Steel and Copper Nanocomposites

$607,393
National Aeronautics and Space Administration
Department of Chemical and Biomedical Engineering
Project: Strain-Tolerant Self-Sensing Environmental Barrier Coating for SiC/SiC Ceramic Matrix Composites and Si_3N_4

$488,111
National Aeronautics and Space Administration
Department of Mechanical Engineering
Project: Non-Destructive Evaluation and Structural Health Monitoring of Advanced Composite Materials and Propulsion Systems

$500,000
National Science Foundation
Department of Civil and Environmental Engineering
Project: Implementation and Assessment of Failure Case Studies in the Engineering Curriculum

$1,082,400
U.S. Department of Energy
Department of Engineering Technology
Project: Wind Spires as an Alternative Energy Source

$507,303
National Aeronautics and Space Administration
Department of Chemical and Biomedical Engineering
Project: Integration of NDE and Finite Element Modeling and Image Visualization

$1,000,000
Betty L. Gordon Endowed Distinguished Professorship & Alternative Energy Research
Fenn College of Engineering

$281,999
American Diabetes Association
Department of Electrical and Computer Engineering
Project: Stabilization of Immobilized Enzymes for Implantable Glucose Monitoring Devices

$474,700
Ohio Board of Regents
Fenn College of Engineering
Project: Engineering Across the Pipeline

$450,000
National Science Foundation
Department of Chemical and Biomedical Engineering
Project: Materials World Network: Synthesis and Characterization of Functional Molecular Building Blocks for Responsive Materials

$389,749
National Aeronautics and Space Administration
Department of Mechanical Engineering
Title: Smart Structural Health Monitoring of Rotating Components Using Active Magnetic Force Actuators

$332,949
National Aeronautics and Space Administration
Department of Chemical and Biomedical Engineering
Project: Planar Optical Diagnostics for Flow Field Measurements and Optical Build Up

$269,849
U.S. Department of Energy
Department of Civil and Environmental Engineering
Project: Modeling Stress Strain Relationships and Predicting Failure Probabilities for Graphite Core Components

$317,341
National Aeronautics and Space Administration
Department of Chemical and Biomedical Engineering
Project: Development of Acoustics, Tomography, and Radiography Sciences and Facilities in Operations

$182,019
National Aeronautics and Space Administration
Department of Chemical and Biomedical Engineering
Project: Propulsion Health Monitoring System Development and Instrumentation

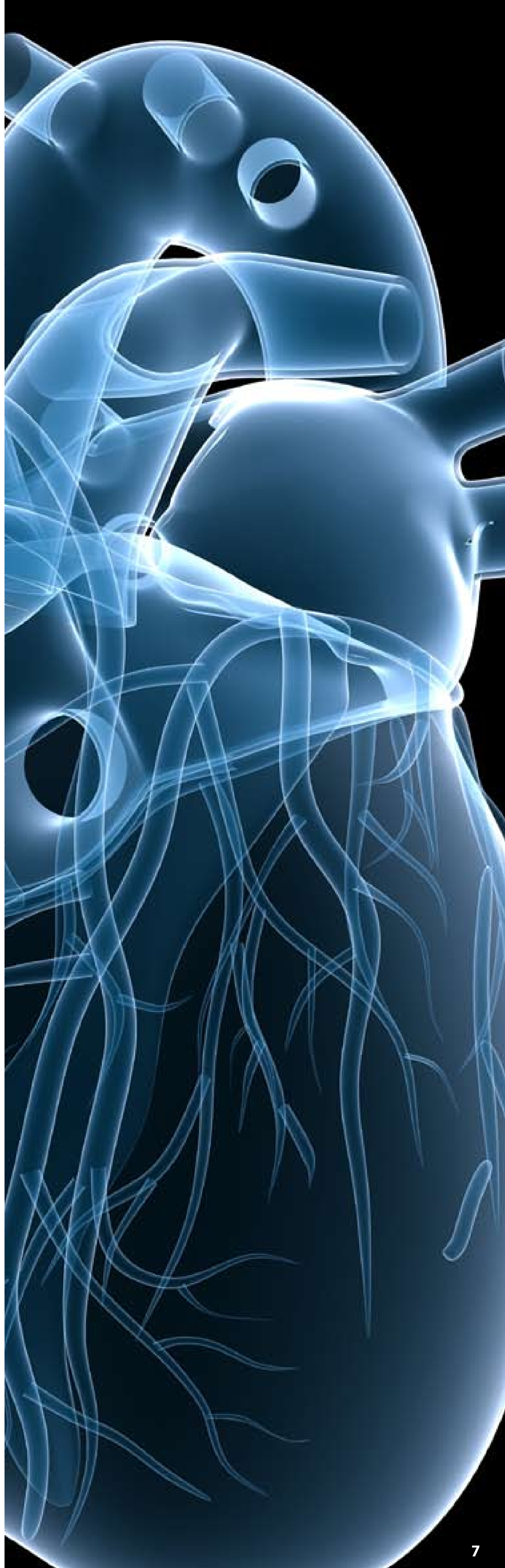
$170,183
Ohio Board of Regents
Fenn College of Engineering
Project: The Fenn Academy Pathways to Engineering-Summer Academy

$166,267
National Aeronautics and Space Administration (through the University of Arizona)
Department of Chemical and Biomedical Engineering
Project: Effect of Convection and Step-Change in Growth Speed on Dendritic Array Morphology During Direction

Biofluid Mechanics and Cardiovascular Imaging

The fields of magnetic resonance imaging and cardiovascular fluid dynamics are central to Professor Chatzimavroudis' research activities. The combination of these fields provides important information for the understanding, diagnosis and treatment of a variety of cardiovascular disease.

GEORGE P. CHATZIMAVROUDIS
Ph.D., GEORGIA INSTITUTE OF TECHNOLOGY
ASSOCIATE PROFESSOR, DEPARTMENT OF CHEMICAL AND BIOMEDICAL ENGINEERING
INTERIM ASSOCIATE DEAN OF OPERATIONS, FENN COLLEGE OF ENGINEERING



Professor Chatzimavroudis has had almost two decades of research experience in the areas of cardiovascular imaging and blood flow dynamics. His work encompasses a large variety of medical and engineering problems, such as:

- studying the reliability of intravascular Doppler ultrasound in coronary artery disease
- developing and validating of new clinical protocols to quantify aortic and mitral valve regurgitation
- optimizing of the total cavopulmonary connection to treat children with congenital heart disease
- evaluating the viscous dissipation method to assess flow energetics non-invasively
- developing magnetic resonance and computer tomography image-based computational fluid dynamics methods
- studying the effect of flow turbulence on the accuracy of magnetic resonance phase velocity mapping
- evaluating ultra-fast magnetic resonance velocity techniques
- optimizing contrast agent injection in cardiovascular computer tomography

He has had more than 85 peer-reviewed journal publications, book chapters, and conference proceedings/presentations. He is the Director of the Biofluid Mechanics and Cardiovascular Imaging Laboratory at CSU and he has supervised/co-supervised the research of 18 doctoral and 17 Master's students and the work of several undergraduate students. He has taught numerous undergraduate and graduate courses in several areas including transport phenomena, fluid mechanics, biofluid dynamics, medical imaging, biostatistics, bio-signal processing, and computer programming.

The field of magnetic resonance phase velocity mapping is central to Professor Chatzimavroudis' research activities. The following section will present his research activities in this area and will provide information about recent results of scientific and clinical significance.

Magnetic resonance imaging provides high-quality structural, functional, and flow information in a non-invasive manner. It is based on the effects of externally applied magnetic fields on the magnetic behavior of a mass containing hydrogen nuclei. Inside a static magnetic field (such as that of a modern clinical magnetic resonance scanner), the hydrogen nuclei tend to be either at a low or at a high energy state. The combination of the static field with the spin of the nuclei results in a rotational motion called precession. This precession has a certain frequency which depends on the strength of the static magnetic field. Using radio-frequency pulses with a frequency equal to this precession frequency (that is the reason for the word *resonance*), the nuclei can be energetically excited or transit between the low and high energy states. While the nuclei return to equilibrium, they emit a signal which is used to reconstruct an image. By applying a combination of magnetic field gradients in all three spatial directions, the position of the excited nuclei can be spatially encoded. The acquired raw data is in the frequency domain; once the necessary amount of data is acquired, an inverse two-dimensional Fourier transform reconstructs the image in the space domain.

An important feature of magnetic resonance is its ability to measure the velocity of a fluid, such as blood, in any spatial direction, using a technique called magnetic resonance phase velocity mapping (MRPVM). Using special bipolar magnetic field gradients, the velocity of the nuclei can be encoded into the phase of the received signal. The magnitude of the acquired signal is used to reconstruct the traditional magnitude (structural) image, whereas the phase of the signal can be used to reconstruct the phase (velocity) image (Figure 1). This unique ability to characterize and quantify flow has found clinical applications for blood flow measurements in the heart, arteries and veins, as well as non-biomedical applications for flow characterization of pure fluids and suspensions, in porous media, in fixed-bed reactors, etc.

In the following sections, some of the recent and current MRPVM-related research work performed by Professor Chatzimavroudis' research group will be described.

HEART VALVE REGURGITATION

The aortic valve is located between the left ventricle of the heart and the aorta. Its function assures adequate blood flow from the heart to body tissues and organs. When healthy, the aortic valve remains completely closed during diastole. Similarly, the mitral valve is located between the left atrium and the left ventricle of the heart. Its function allows blood to fill the left ventricle during diastole. When healthy, the mitral valve remains completely closed during systole. However, because of a variety of reasons, these valves may not close completely allowing some blood to flow in the opposite direction. This disease is called valvular (aortic or mitral, in this case) regurgitation and it affects cardiac function, leading to death in severe cases if untreated.

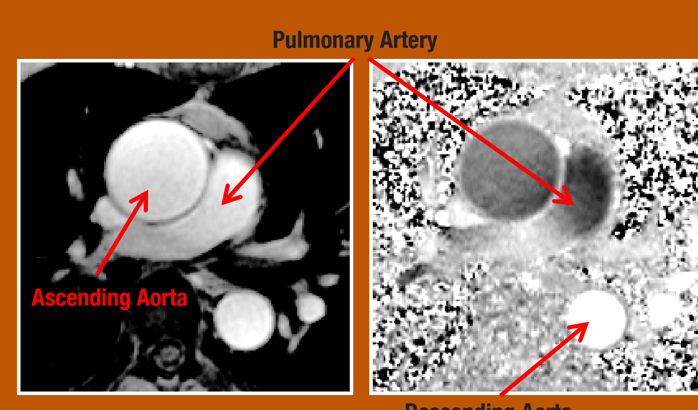


Figure 1: Magnitude (left) and phase (right) images from an MRPVM acquisition in a patient with dilation of the ascending aorta. The phase image contains velocity information.

A variety of clinical techniques have been used in the past to assess the presence and severity of aortic regurgitation. Techniques such as angiography and echocardiography can provide mainly qualitative information about the disease; however, many factors may severely affect their reliability. MRPVM can measure directly the amount of blood that regurgitates, by placing an imaging slice in the ascending aorta (Figure 2), thus providing a more direct diagnostic index for the severity of the disease. Professor Chatzimavroudis has had a long experience studying the potential of MRPVM in aortic regurgitation. In his earlier studies, he investigated the effects of aortic compliance and coronary flow on the accuracy of the MRPVM measurements. Recently, he and his research group in collaboration with physicians and scientists at the Cleveland Clinic evaluated the potential of ultra-fast (segmented k-space) MRPVM techniques to quantify blood flow in the ascending aorta of patients with aortic regurgitation. These rapid techniques reduce the data acquisition time from minutes to only seconds. In vitro and in vivo studies showed that segmented k-space MRPVM is very accurate (in vitro errors<5%) and has great clinical potential in aortic regurgitation.

The quantification of mitral regurgitation is more complicated, because a single imaging slice is not enough to quantify the regurgitant flow. Professor Chatzimavroudis investigated the potential of a sophisticated multi-slice control volume method and found that it has a lot of potential in mitral regurgitation. Recently, he and his research group focused on one of main limitations of the control volume method, which is its long duration. They evaluated the potential of rapid MRPVM in implementing the control volume method and found close agreement between the rapid (duration of <10 minutes) and conventional (duration of > 45 minutes) MRPVM.

Current studies are focusing on clinical factors which may affect the reliability of MRPVM in order to reach the point of routine clinical implementation to the diagnosis of heart valve regurgitation.

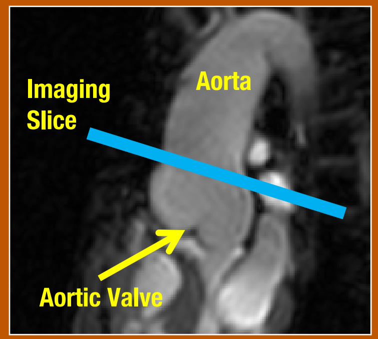
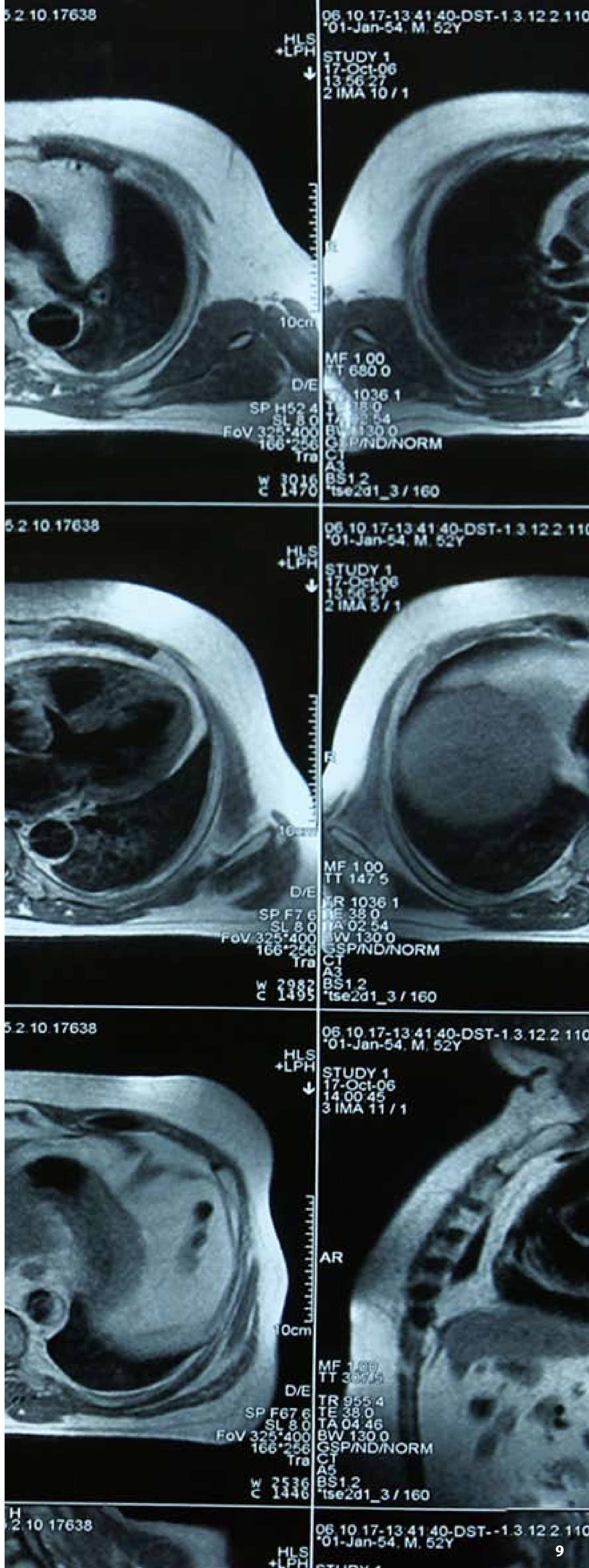


Figure 2: Magnetic resonance image of the ascending aorta and imaging slice placement for MRPVM measurement of the aortic regurgitant flow.



TOTAL CAVO-PULMONARY CONNECTION

Congenital heart disease is the most common type of heart disease in children. Surgical repair is essentially the only survival option. Currently, the commonly-followed procedure is the total cavopulmonary connection (TCPC), which involves a surgical connection of the superior and inferior venae cavae directly to the right pulmonary artery, creating the configuration shown in Figure 3.

The design of the connection is crucial to post-operative survival and quality of life. Several in vitro, numerical, and in vivo studies have investigated the optimization of TCPC, mainly focusing on the reduction of the fluid mechanical energy losses of blood as it flows through the connection and on the proper blood flow distribution to the lungs. Professor Chatzimavroudis has been involved in TCPC optimization over the last 15 years. His recent research work has focused on a non-invasive approach to measure the TCPC energy losses using MRPVM. By applying the viscous dissipation method, the energy loss can be calculated only through velocity measurements, without the need for invasive pressure measurements. Recent results by Professor Chatzimavroudis' research group have shown that the viscous dissipation method has great potential as shown by the agreement between MRPVM and computational studies.

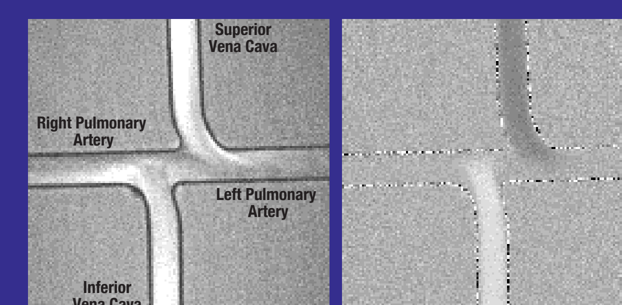


Figure 3: TCPC configuration as shown in magnitude (left) and phase (right) MRPVM images. These images were acquired from glass TCPC models. The phase (velocity) image shows the velocity component in the inferior-superior direction.

Figure 4: Image-based reconstructed geometry of an aortic model, showing the aortic arch (left) and the non-planar nature of the geometry (right).

IMAGE-BASED COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) is a well-evaluated tool to study fluid mechanics. It is widely used to study cardiovascular fluid mechanics, based on its practicality and reliability. One of CFD's potential applications is the reconstruction of individual-specific geometries which would be used to perform flow simulations relevant to a specific individual's condition. Clinical imaging modalities, such as magnetic resonance imaging can be very helpful to reconstruct the geometry and provide flow boundary conditions for the simulations. Professor Chatzimavroudis and his research group have recently studied this potential of image-based CFD, by imaging in vitro models of the ascending aorta (Figure 4) and the carotid artery bifurcation, reconstructing the geometry, and perform CFD simulations. The results showed close agreement between the MRPVM velocity profiles and the image-based CFD computed velocity profiles as seen in Figures 5-7.

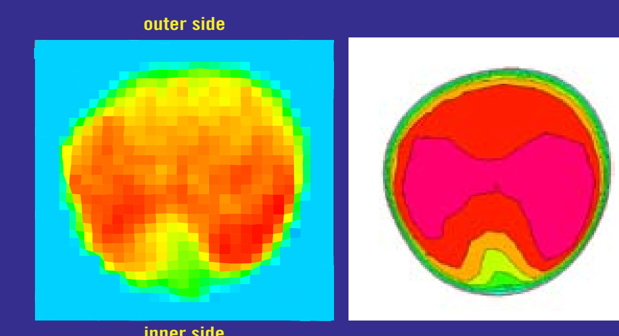


Figure 5: Through-plane velocity at the top of the arch of the aortic model: left, MRPVM velocity data; right, image-based CFD velocity data.

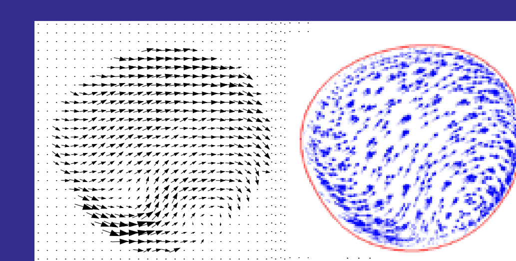


Figure 6: In-plane velocity vector plots at the top of the arch: left, MRPVM velocity data; right, image-based CFD velocity data.

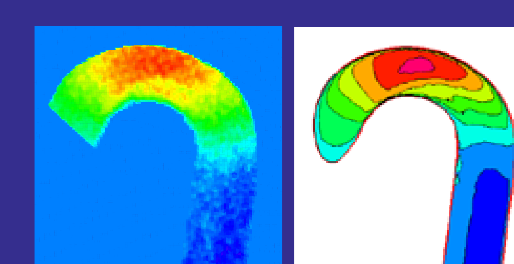


Figure 7: Centerline velocity plots through the descending part: left, MRPVM velocity data; right, image-based CFD velocity data (arrow shows the velocity encoding direction).

Failure Analysis and Concrete Technology

Professor Delatte's latest NSF grant will expand his work to other colleges and universities across the US in order to assess the impact of including failure case studies in engineering course work at different institutions.

NORBERT DELATTE
Ph.D., THE UNIVERSITY OF TEXAS, P.E., F.ACI
PROFESSOR, DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

FAILURE ANALYSIS AND FAILURE CASE STUDY INTEGRATION INTO THE ENGINEERING CURRICULUM

Through Professor Delatte's projects, funded by — among other sources — the National Science Foundation, a series of failure case study workshops have been held for faculty at many locations in the United States as well as in the United Kingdom and Costa Rica. These research projects have produced a number of published failure case studies. In 2008, the case studies were collected in the book titled, "Beyond Failure", published by ASCE Press.

This research also produced a project web site, http://matdl.org/failurecases/, which is part of the NSF Materials Digital Library. The web site includes a master bibliography, a discussion of the faculty case study workshops, a chronological listing of case studies, a list of course pages, and information for faculty.

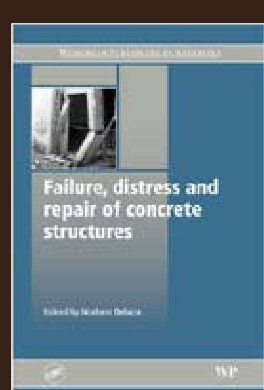
Professor Delatte's latest NSF grant will expand this work to eleven other colleges and universities across the US in order to assess the impact of including failure case studies in engineering course work at different institutions.

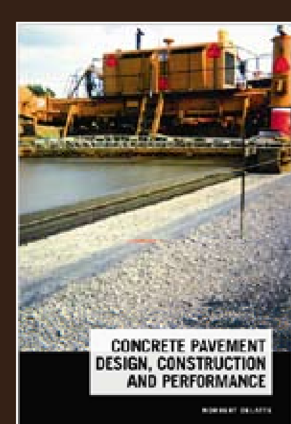
CONCRETE TECHNOLOGY

Professor Delatte research has focused on examining ways to reduce the cracking of concrete bridge decks so that they would last longer and require less maintenance. Through his research, Cleveland State University has become a national leader in the important technology of pervious concrete pavement. Pervious concrete allows water to flow through into a drainage or holding system, reducing stormwater impacts such as flooding. The figures below show two pervious concrete test sites built at Cleveland State University which showed good performance.

In addition to his research, Professor Delatte has been very active authoring/editing books in his area of expertise.

Pervious concrete test sites at Cleveland State University, built 2005 and 2007





Books in concrete technology

Better Control Systems for MEMS Gyroscopes

After comparing and analyzing all of the available controllers, Professor Dong with her associates have found a practical solution to control MEMS gyroscopes based on the Active Disturbance Rejection Control technology.

LILI DONG

Ph.D., THE UNIVERSITY OF ALABAMA

ASSISTANT PROFESSOR, DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Professor Dong's research group focuses on developing a novel control strategy for high-performance and low-cost micro electro-mechanical systems (MEMS) gyroscope for commercial applications. MEMS gyroscopes are micro-scaled or millimeter-scaled inertial rate sensors. They play an important role in the automobile industry (rollover detection, anti-sliding control and GPS), aerospace (GPS assisted inertial navigation), and consumer electronics (camera image stabilization, cell phone GPS, and 3-D mouse). Compared to traditional electro-mechanical gyroscopes, the MEMS gyroscopes are small in size, inexpensive, and energy efficient. However, the imperfection of micro-fabrication and the presence of surrounding disturbances degrade their performance and cause measurement errors. Therefore, a robust control system is essential for improving their performance by compensating for the fabrication imperfections and disturbances.

After comparing and analyzing all of the available advanced controllers, Professor Dong with her associates from Cleveland State University and Case Western Reserve University have found a practical solution based on the Active Disturbance Rejection Control (ADRC) technology. ADRC is very robust against noises and disturbances and easy to implement. In the first phase of this project, the hardware implementation of the ADRC has been successfully completed on a beam gyroscope using pure analog circuits. The ADRC solution has proved to be simple, easy to tune, and most importantly, economical. The experimental setup and calibration data are shown in Figures 1 and 2.

Compared to the MEMS gyroscope available in the market, the operation range of the ADRC beam gyroscope is increased twice, the response time is greatly decreased from 35 ms to 10 ms, and the sensitivity is significantly improved via reducing the approximation error of the rotation rate from 0.1% to 0.001%. Experimental results have demonstrated the effectiveness of the control solution and the improved performance of the MEMS gyroscope.

Professor Dong and her associates have started the commercialization phase, exploring commercial partnerships to bring this R&D project to its next level which includes prototyping, small quantity production, and field tests. The Center for Advanced Control Technologies (CACT) and the MEMS research laboratory at Cleveland State University provide support for the simulations, circuit layouts and manufacturing, as well as bench test personnel and equipment.

Figure 1: Experimental setup photo of vibrational beam gyroscope and rate table

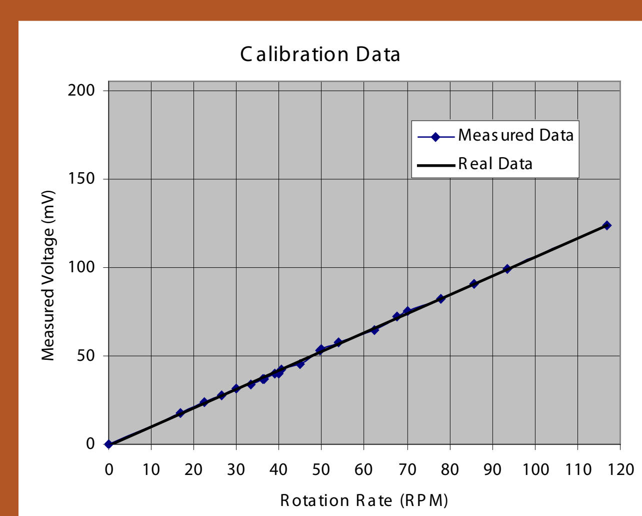
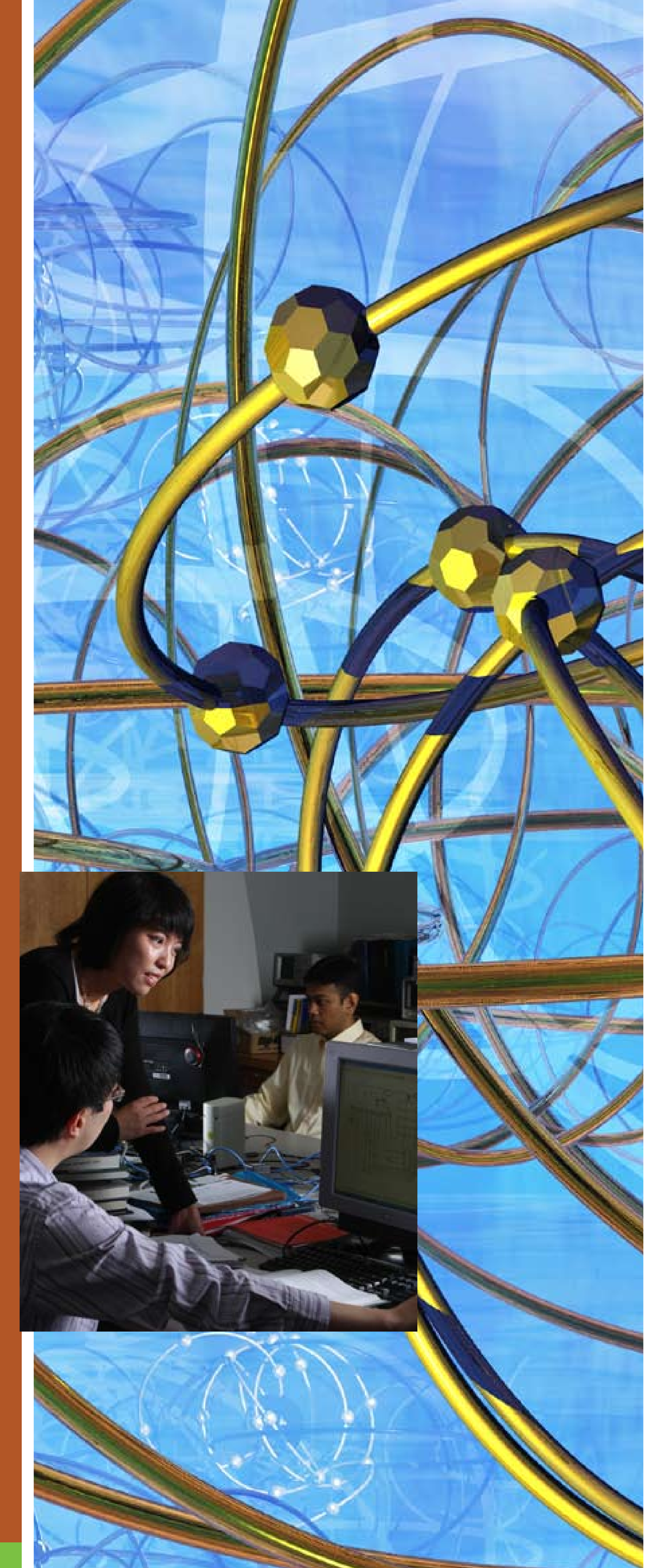
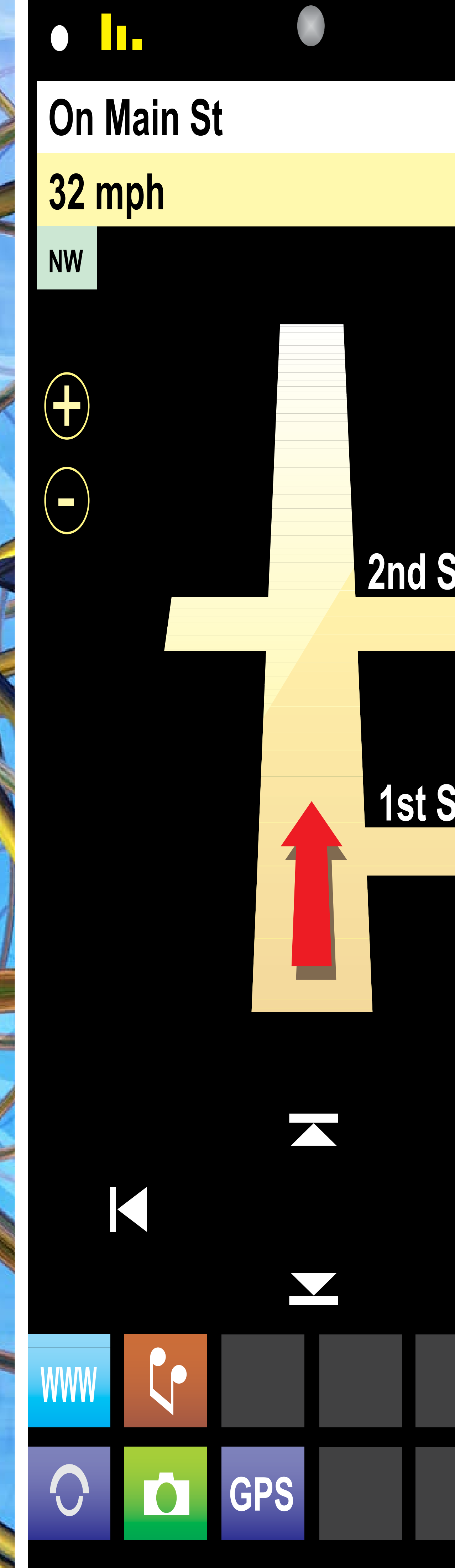
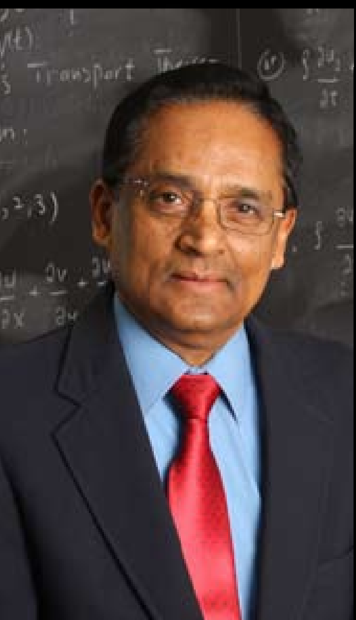


Figure 2: Calibration data between the rotation rates of the rate table and the output voltages of the beam gyroscope





Storage and Transport of Liquefied Natural Gas



Professor Gorla and his research group have examined several technical problems concerning the storage and transport of liquefied natural gas, such as the thermal stress distribution. He has also used probabilistic methods to analyze the unsteady aerothermodynamics of turbomachinery and predict system failure.

RAMA S.R. GORLA
Ph.D., THE UNIVERSITY OF TOLEDO
FENN DISTINGUISHED RESEARCH PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING

Natural gas is one of the most effective means of coping with today's energy crisis. It finds many applications including heating, cooling and electric power generation. It offers an energy density comparable to petroleum and diesel fuels and produces less pollution. The demand for natural gas has increased five times in the last few decades because it is easily transportable and environmentally friendly.

Liquefied Natural Gas (LNG) is natural gas that has been cooled to -163º Celsius. In its liquid state, LNG is reduced to approximately one-six hundredth (1/600th) of its volume compared to the gaseous form. This makes it easier to be stored and transported safely and reliably to all corners of the globe. Once LNG reaches its destination, it is regasified and distributed as pipeline natural gas. Professor Gorla and his research group have examined several technical problems concerning the storage and transport of LNG, such as the thermal stress distribution as shown in Figure 1.

Professor Gorla and his group have also been active in several other areas of research. Specifically, he has studied heat and mass transfer mechanisms in evaporating thin films (Figure 2) and in non-Newtonian fluids. He has also used probabilistic methods to analyze the unsteady aerothermodynamics of turbomachinery and predict system failure (Figures 3 and 4).

A research field with applications in geothermal engineering, insulation systems, and petroleum recovery which Professor Gorla has investigated is mass and energy transfer in porous media using Newtonian and non-Newtonian fluids. In fact, he is co-authoring a text book on heat and mass transfer in porous media. He and his group are also interested in heat transfer from slotted surfaces. The focus is on the study of the boundary layer flow over a slotted plate with emphasis on the validity or not of the non-slip assumption. He and his students have also been investigating heat and mass transfer in boundary layer flows of nanofluids past several geometries embedded in porous media.

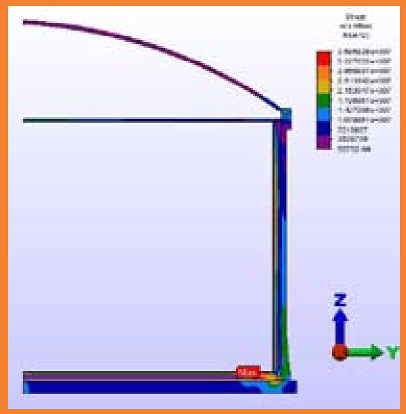


Figure 1: Thermal Stresses in an LNG Storage Tank

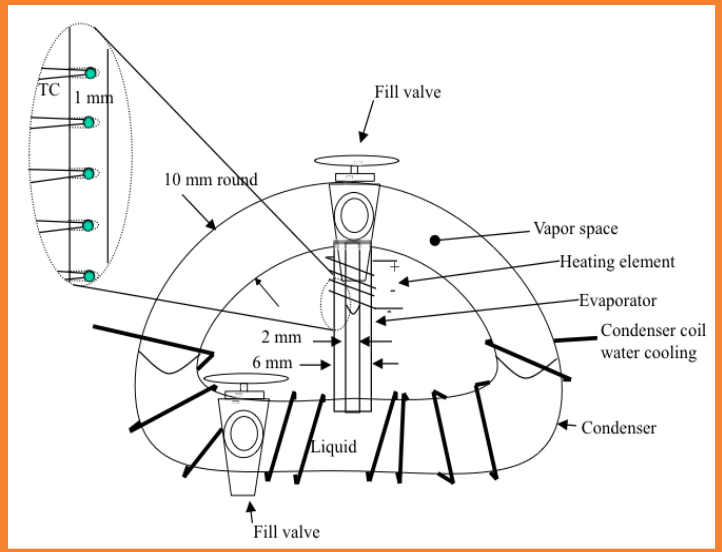


Figure 2: Experimental set up for evaporating film - the interfacial thermocapillary stresses arising from liquid-vapor interfacial temperature gradients can be counteracted by introducing naturally occurring concentration gradients associated with distillation in binary fluid mixtures without affecting the heat transport capacity of the system

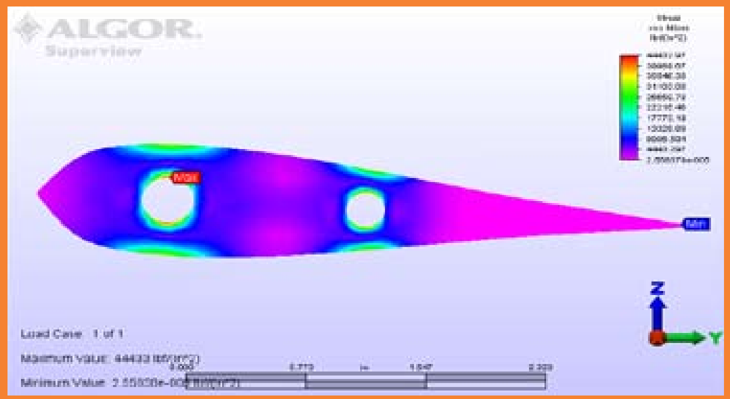


Figure 3: Thermal Stresses in a Turbine Blade

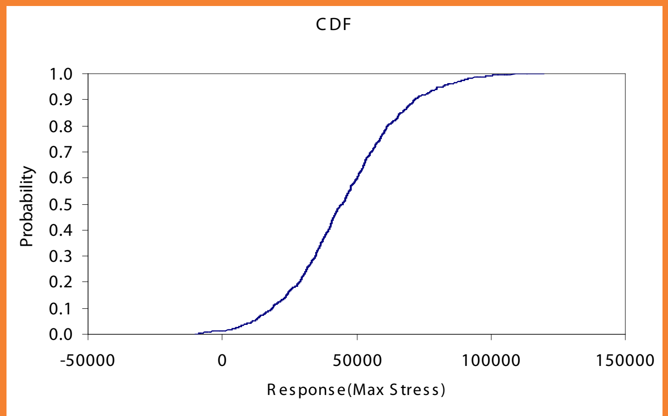
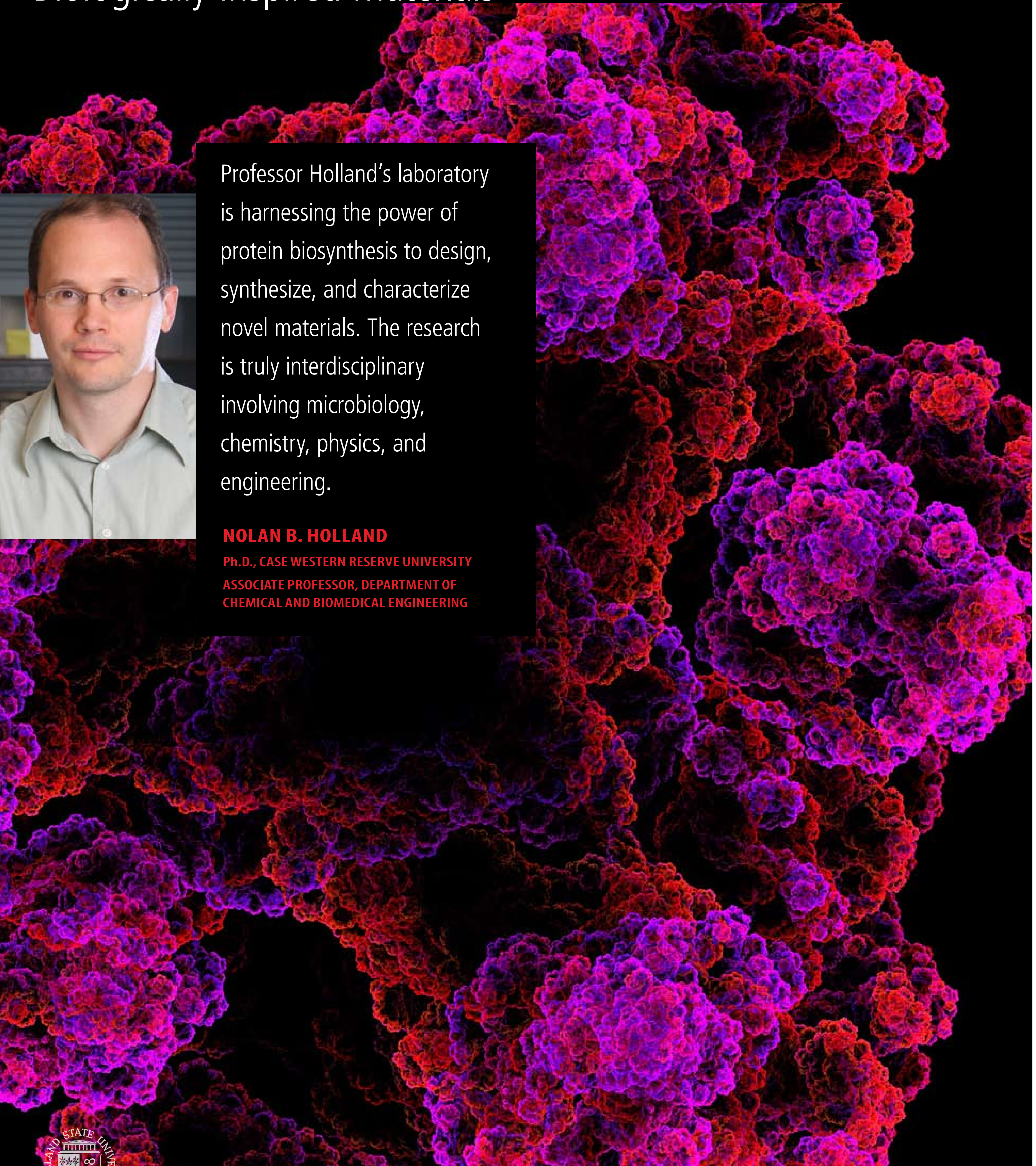


Figure 4: Cumulative Distribution Function (CDF) for Maximum Stress

Biologically Inspired Materials



Professor Holland's laboratory is harnessing the power of protein biosynthesis to design, synthesize, and characterize novel materials. The research is truly interdisciplinary involving microbiology, chemistry, physics, and engineering.

NOLAN B. HOLLAND

Ph.D., CASE WESTERN RESERVE UNIVERSITY

ASSOCIATE PROFESSOR, DEPARTMENT OF CHEMICAL AND BIOMEDICAL ENGINEERING

Long before we entered the age of synthetic polymers, mankind had been using polymers that were produced by nature. As a structural material, wood consists primarily of the natural polymers cellulose, hemicellulose, and lignin. Likewise, natural fibers, such as cotton and linen, are predominantly cellulose, which is a polysaccharide that is the most abundant organic compound on earth. In addition to polysaccharides, plants produce other commercially important polymers such as natural latex rubber. Polymers from animal sources include polysaccharides, such as chitin from shellfish and insects, and protein-based materials. The protein collagen is the most prevalent component of many protein-based materials including ivory, leather, sinew, and gelatin, but other proteins, such as silk and keratin, also come from animals.

During the last century, great work has been done to replace natural materials with lower cost synthetic polymers. Thermoset polymers replaced ivory in billiard balls. Vinyl polymers have substituted leather. One of the major driving forces for the development and commercialization of new synthetic polymers was World War II. Newly developed synthetic rubbers were used to replace natural rubber when its supply from Southeast Asia was cut off, nylon was used to replace silk for parachutes, tents and ropes, and Plexiglas was used for airplane canopies. The development and use of synthetic polymers after the war increased dramatically, particularly since they often can be produced at a much lower cost and in a greater abundance than natural materials. In fact, one may argue that synthetic polymers, more than anything else, improved the standard of living during the latter half of the 20th century.

As we begin the 21st century, Professor Holland's Biologically Inspired Materials Laboratory of the Fenn College of Engineering at Cleveland State University is continuously looking to nature for inspiration in the development of new functional materials. Functional materials are those that are not simply passive but respond to its environment in a predictable and useful manner. As a class of functional materials, stimuli-responsive materials (often referred to as "smart" materials) can respond to environmental cues to change shape, volume, or other property.

Of the three natural organic polymers, which are common to all life on earth – nucleic acids, proteins, and polysaccharides – proteins are of particular interest for developing functional materials. The control of protein synthesis by cells is the envy of many polymer chemists – each type of protein is a monodisperse polymer with an identical configuration of the 20 natural amino acids. This control of structure results in natural proteins that fold into a single low energy three-dimensional conformation. This 3-D structure is important, because it allows a protein to carry out one of the numerous functions that proteins perform in the body, including providing structure, catalyzing reactions, carrying compounds, signaling, etc. Professor Holland's laboratory is harnessing the power of protein biosynthesis to design, synthesize, and characterize novel materials. Two areas that are described below are developing responsive hydrogels of elastin-like polypeptides and using antifreeze proteins to stabilize ice slurries used as functionally thermal fluids. The research is truly interdisciplinary involving microbiology, chemistry, physics, and engineering. The students who perform the research range from high school students working on short-term projects to advanced doctoral students.

In order to have precise control over protein-based materials, Professor Holland's group uses a biological system to synthesize their products – namely, the bacteria Escherichia coli. E. coli is best known for causing food poisoning, but it is just a few strains that give it a bad name. Most strains are harmless and even live in the intestines of animals. The strain of E. coli used is one that has been developed to efficiently express (i.e. synthesize) recombinant proteins. This is accomplished by inserting DNA that codes for a specific protein into the bacteria, growing a culture of the modified bacteria, and adding a chemical that induces the protein expression. The protein is then retrieved by breaking the cells apart and purifying the protein. From one liter of bacterial culture, a yield of over 100 mg of purified protein can be obtained.

The recombinant DNA which is inserted into the bacteria is the key to getting the desired product. The bases of the DNA encode the sequence and length of the protein to be produced. Once the desired protein structure is determined, the appropriate DNA is designed and then standard molecular biology techniques are used to generate the DNA.

ELASTIN-LIKE POLYPEPTIDES FOR RESPONSIVE MATERIALS

A major thrust of Professor Holland's research is the design of new responsive materials. His approach is to use polypeptides (i.e. protein-based polymers) that are repeats of five amino acid sequences found in the protein elastin. As the name suggests, elastin is a structural protein that provides elasticity to various animal and human tissues such as skin and arteries. The elastin-like polypeptides (ELPs) can be used to form hydrogels that also exhibit elastic type behavior. Hydrogels are networks of cross-linked water-soluble polymers that swell in the presence of aqueous solutions. Common examples include soft contact lenses and gelatin. When swollen, hydrogels can contain over 95% water. The high water content and rubber elasticity of these materials mimic the properties of biological tissues, making them ideal as biomaterials and tissue engineering scaffolds.

Another important characteristic is that the hydrogels can transition reversibly from the swollen conformation to a collapsed conformation. The volume of the gel and the mobility of the chains in the two states can be considerably different. This transition can occur based on different environmental changes – e.g. temperature, pH, chemical species – leading these materials to be called stimuli-responsive materials, "smart" or "intelligent" hydrogels, and functional materials. Because these materials act to convert various forms of energy to mechanical energy, they can be utilized as thermo-mechanical, opto-mechanical, or chemo-mechanical transducers.

Responsive hydrogel materials have found wide application in areas including drug delivery, chromatographic separations, biosensors, biomaterial self-assembly, flow controls in microfluidic devices, and optical switches. The two most widely studied and utilized systems are the synthetic polymer PNIPA (poly-N-isopropylacrylamide) and ELPs. A major advantage of using ELPs is that biosynthesis provides control of their properties by changing the amino acid sequence and length of the polypeptides. This allows materials that convert energy between different forms to be more easily designed.

One of the major limitations of the responsive hydrogels is that the rate of change is typically slow. The time constant for collapsing or swelling of the gel is proportional to the square of the smallest dimension of the gel. For gels as small as 1/10th of a millimeter, the collapse might only take minutes, whereas one that is one centimeter would take weeks. This slow response is a result of the arrangement of the polymer chains in the hydrogel. To collapse, the polymer chains need to find neighboring chains, aggregate, and expel water. In the hydrogel these chains are randomly arranged, so these steps require significant amounts of time.

Professor Holland's lab is designing polymers that arrange differently at the molecular level in order to increase the rate that the hydrogels collapse. By connecting three ELP polymers at their ends, the chains can more easily find each other and assume the collapsed conformation. To connect the chains, natural protein structures that assemble as trimeric units have been utilized. One is the foldon domain from a viral protein and the second is a three-peptide repeat from collagen proteins. Using recombinant techniques, foldon and collagen domains have been added to ELPs to make new polypeptides.

Supported by a collaborative grant of the National Science Foundation and the German Science Foundation, Professor Holland's group is working together with the research group of Prof. Dr. Thorsten Hugel at the Technical University of Munich in Germany to characterize these new constructs and to assemble them into new materials. The goal is to demonstrate that these novel constructs can be used as molecular scale transducers, establishing a new foundation for the development of fast responsive materials for nano-machines, sensors, drug-delivery devices, and other specialty applications.

FUNCTIONALLY THERMAL FLUID: ANTIFREEZE PROTEIN STABILIZED ICE SLURRIES

Antifreeze proteins (AFPs) are another protein system that Professor Holland's group is working with. AFPs help organisms that live in cold climates survive freezing temperatures. Since their discovery in Antarctic fish almost forty years ago these proteins have intrigued and baffled scientists. They function by binding to specific surfaces of ice crystals, which can slow down or completely prevent the crystals from growing. This effectively reduces the temperature at which ice crystals grow in antifreeze solutions. However, the proteins do not correspondingly reduce the melting temperature of ice, leaving a temperature gap between the melting and freezing point (termed thermal hysteresis) where the ice will neither freeze nor thaw. Within this temperature window, the proteins prevent ice recrystallization, i.e. the growth of large crystals at the expense of smaller ones (Ostwald ripening). Because of this ability to stabilize ice solutions, antifreeze proteins have been approved as a frozen food additive. Professor Holland's lab is actively investigating ways that AFPs also can be used to extend the storage life of transplant organs and designing more effective AFPs for stabilizing ice slurries used as thermal fluids used to improve efficiency of refrigeration and air conditioning systems.

Functionally thermal fluids are heat transfer fluids that have increased heat storage due to the latent heat of a phase change. The higher heat capacity per volume reduces the amount of fluid needed and increases efficiency in heat exchangers, thereby reducing costs associated with pumping of the fluids. Ice slurries are suspensions of small ice crystals in aqueous solution that still flow like a liquid, such as frozen drinks. Ice slurries systems are one of the most effective functionally thermal fluids because of the large latent heat of ice absorbed during melting. One of the biggest challenges for using ice slurries is that ice crystal growth and recrystallization can lead to increased viscosity and clogging in pipes, valves, and pumps. Because of their ability to prevent ice growth and recrystallization within the thermal hysteresis window, antifreeze proteins could be used as an additive to stabilize ice slurry systems.

A barrier to the use of antifreeze proteins in ice slurries is their high cost. An approach to solve this problem is to design new AFP constructs with much greater effectiveness (as much as 100 times), so that the same activity can be achieved with only a fraction of the protein. This is accomplished by producing constructs with multiple binding regions to increase the avidity for the ice surface. One approach is to use protein engineering to add the trimer-forming foldon domain to an antifreeze protein. The foldon forms homotrimers resulting in a single construct with three ice binding sites. Constructs with even more binding sites can be produced by conjugating as many as fifty antifreeze proteins to a polymer chain. These new constructs have been shown to significantly increase the activity of the AFPs, especially at low concentrations, which is ideal for ice slurry stabilization.

Advanced Power Conversion Systems

Recently, NASA selected Professor Ibrahim as one of ten principal investigators to receive an award for radioisotope-based power-conversion technologies for research and development. The technologies are intended for use in improved radioisotope-power systems, which could provide higher efficiencies and power levels than those used on existing devices, enabling more sophisticated science instruments and spacecraft subsystems.

MOUNIR IBRAHIM
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PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING

Professor Ibrahim's research activities at CSU have been in the following areas: 1) Active Flow Control in Low Pressure Gas Turbines, 2) Heat Transfer in Gas Turbines, 3) Gas Turbine Combustors, 4) Stirling Engines, 5) Plastic Thermoforming Applications and 6) Thermal Energy Storage Systems. These activities have been funded by the U.S. Government, Industry, and non-profit Organizations (over $5 million of funding). Over 60 students graduated under Professor Ibrahim's supervision with Doctoral and Master's degrees. Professor Ibrahim's research has been published extensively (over 100 publications) in prestigious scientific journals (e.g., *AIAA Journal, AIAA Journal of Propulsion and Power, AIAA Journal of Spacecraft and Rockets, AIAA Journal of Thermophysics and Heat Transfer, Applied Scientific Research, Chemical Engineering Communications, Computers and Fluids, Energy, Int. J. of Heat and Fluid Flow, Int. J. Heat and Mass Transfer, Int. J. of Turbo and JetEngines, Letters Int. Heat Transfer Journal, Transaction of the ASME, Journal of Solar Energy Engineering*, etc.) and in non-scientific journals and magazines (e.g., *On-Campus, Fenn Focus, CSU Perspective, The Plain Dealer, Crain's Cleveland Business, The New York Times*, etc.).

ACTIVE FLOW CONTROL IN LOW PRESSURE GAS TURBINES

Boundary layer separation on the suction side of low-pressure turbine (LPT) airfoils can occur due to strong adverse pressure gradients. The problem becomes more severe as airfoil loading is increased. If the boundary layer separates, the lift from the airfoil decreases and the aerodynamic loss increases, resulting in a drop in overall engine efficiency. A significant increase in efficiency could be achieved if separation could be prevented or minimized. Active flow control could provide a means for minimizing separation under conditions where it is most severe (low Re), without causing additional losses under other conditions (high Re). Minimizing separation will allow for improved designs with fewer stages and fewer airfoils per stage to generate the same power.

In a project funded by NASA, different cases were examined experimentally and computationally to study LPT flow control using pulsed Vortex Generator Jets (VGJ) for the L1A airfoil. Figure 1 shows an airfoil with VGJ holes and the cross section of the hole geometry. These cases represent a combination of variation in Reynolds number, based on the suction surface length and the nominal exit velocity from the cascade, blowing ratio, dimensionless frequency and duty cycle. The data was obtained for the pressure distribution along the airfoil and downstream in the wake as well as for velocity profiles at six different stations downstream of the suction peak. Computational fluid dynamics (CFD) simulations was performed with Large Eddy Simulation (LES) utilizing a finite-volume code (ANSYS Fluent). CFD did provide further insight to better understand the physics of flow control. The results clearly illustrate how a separation bubble will persist at the lower frequency case and that the disturbances created from the jet flow do not have enough energy or time to travel further downstream to cause reattachment. On the other hand, the higher frequency case did exhibit a penetration of the disturbance created by the jet into the separated region and caused reattachment, especially at the trailing edge. It appears that the jet was capable of breaking the large bubble into smaller ones with reattachment in between.

COMPUTATIONAL SIMULATION OF CYLINDRICAL FILM HOLE WITH JET PULSATION ON FLAT PLATES

Film cooling has been used in modern gas turbines to protect the surface of turbine blades from failing at high temperatures. Much research has been done in film cooling in order to achieve better cooling of gas turbine blades and thus increase performance of turbine engines by allowing higher inlet temperatures. About 20-25% of compressor air is used for cooling high performance turbine engines. Higher engine efficiency may be obtained by minimizing coolant mass flow with the same or higher film cooling effectiveness. Experimental studies, found in the literature, showed that coolant flow pulsation might help to improve film cooling, while reducing the actual film flow rate.

In a project supported by the Department of Energy, Professor Ibrahim and his research group investigated different CFD cases for Cylindrical Film Hole (CFH) and film hole with Laterally DIFFused (LDIFF) exit geometries to study the film cooling of flat plates. Those cases included different blowing ratios and both steady flow and pulsed jets. In the jet pulsation cases, the Duty Cycle was taken 50% and the Strouhal number ranged from 0.0119 to 1.0. Fluent commercial code with realizable k - ε turbulence model was used in this study to investigate how the pulsed jet performance was affected by varying: 1) pulsation frequency, 2) blowing ratio and 3) jet geometry. Figure 2 (St=0.38) shows how the jet breaks up due to both the jet left-off and pulsation which provides a continuous supply of coolant on the top surface and thus higher effectiveness at all x/D value (compared to steady state).

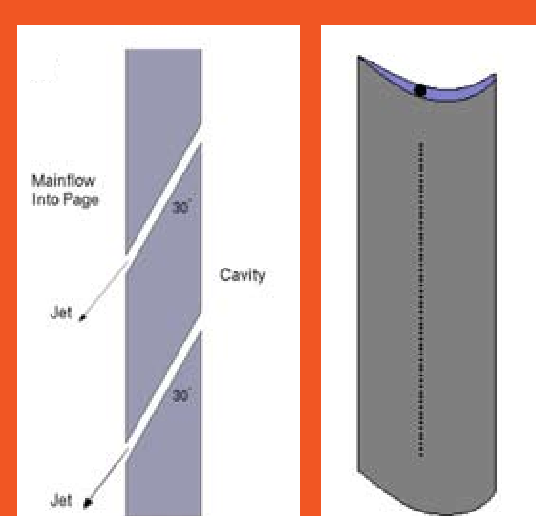


Figure 1: Airfoil with VGJ holes and cross section of hole geometry.

Although pulsation did not bring overall benefit to film cooling, there were cases where pulsed jets helped to increase effectiveness over the steady state conditions. Therefore, present results might be useful for evaluation of the effect of pulse frequency on film cooling effectiveness in real life applications, where jets pulse naturally due to the pressure fluctuations in the engine.

GAS TURBINE COMBUSTORS

Fuel combustion in Gas Turbine has received a lot of attention to improve the quality of combustion as well reduce NOX. Therefore this study focused on the dynamic response of fuel nozzles for liquid-fueled Gas Turbine Combustors and examining the spray characteristics of a Gas Turbine Research nozzle with high frequency flow modulations. Furthermore an Airblast-Simplex Nozzle was designed at Parker Hannifin Corp. The spray characteristics for that nozzle was examined, Experimentally, at NASA GRC (Lewis at that time) using PDPA (Phase Doppler Particle Analyzer) and Computationally, at CSU using CFD-ACE+ Commercial Code.

STIRLING ENGINES RESEARCH

Recently, NASA selected several radioisotope-based power-conversion technologies for research and development (R&D). The awards are the first competitive technology procurement funded entirely by NASA's Project Prometheus. These systems are distinguished by their use of new technologies for converting heat from radioisotope fuel into electrical power. The technologies are intended for use in improved radioisotope-power systems, which could provide higher efficiencies and power levels than those used on existing devices, enabling more sophisticated science instruments and spacecraft subsystems. The awards cover several distinct power-conversion technology areas: Thermoelectrics, Thermophotovoltaics, Stirling Engines, and Brayton Engines. Stirling Cycle Engines (SCE) have the potential of achieving efficiencies three-to-four times greater than existing systems. SCE have been used in space for sensor cooling and cryogenic storage. Professor Ibrahim was selected to receive a three-year award as one of the 10 principal investigators for his project titled "Developing the Next-Generation Stirling Engine Regenerator: Designing for Application of Microfabrication Techniques and for Enhanced Reliability and Performance in Space Applications".

A major outcome of this effort resulted in designing, manufacturing and testing of a Microfabricated Segmented-Involute-Foil Regenerator for Stirling Engines (Figure 3). The concept consists of stacked involute-foil nickel disks microfabricated via a lithographic process (Figure 4). Test

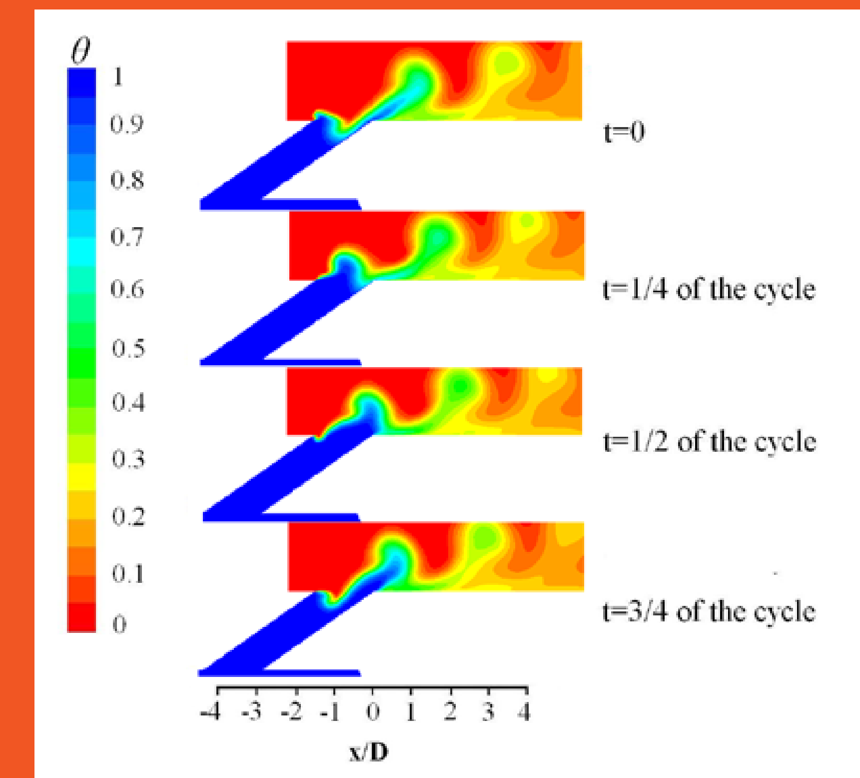


Figure 2: Dimensionless temperature sideview, Blowing Ratio = 1.5, Cylindrical Film Hole Geometry, Strouhal Number = 0.38, shown at different times during pulsed jet blowing.

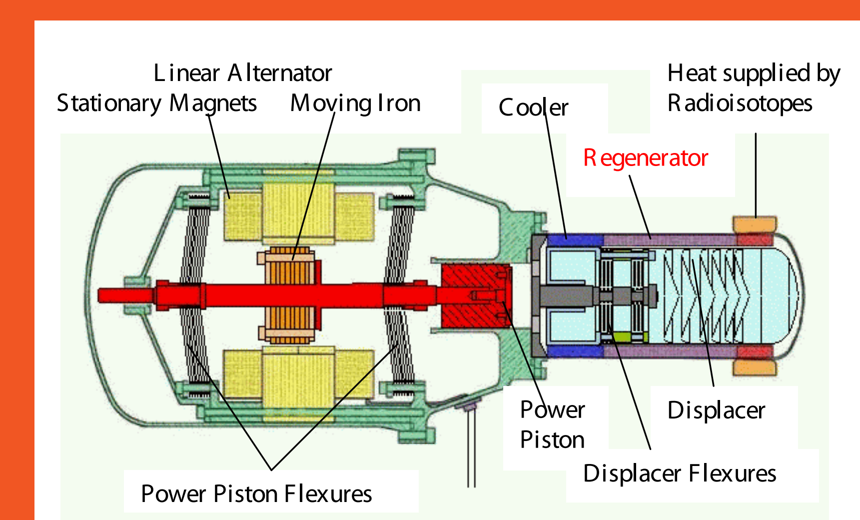


Figure 3: Schematic of Stirling convertor showing the location of the regenerator.

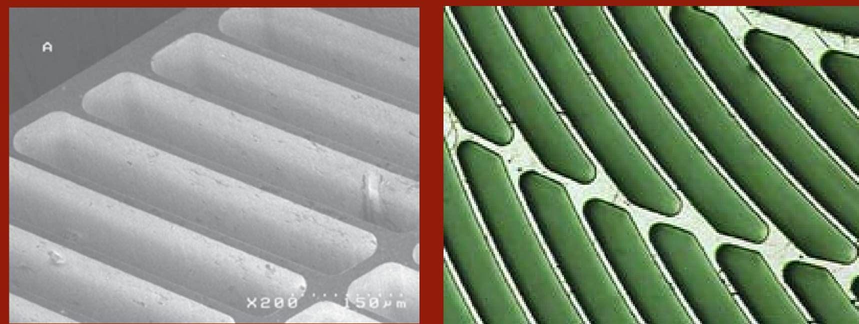


Figure 4: Micrograph of regenerator disks during the final steps of fabrication.

results yielded a Figure-of-Merit of about twice that of the 90-percent random-fiber currently used in small Stirling converters. The segmented nature of the involute-foil in both the axial and radial directions increases the strength of the structure relative to wrapped foils. In addition, relative to random-fiber regenerators, the involute-foil has a reduced pressure drop, and is expected to be less susceptible to the release of metal fragments into the working space, thus increasing reliability. The prototype nickel involute-foil regenerator was adequate for testing in an engine with a 650 ºC hot-end temperature. This is lower than that required by some high temperature engines, and high-temperature alloys are not suited for the lithographic microfabrication approach. This work was performed by Professor Ibrahim and his group at CSU in collaboration with researchers at the University of Minnesota, Gedeon Associates, Infinia Corp., Sunpower Inc., and International Mezzo Technologies under the supervision of the NASA Glenn Research Center. For more information, please download the Technical Support Package (free white paper) at www.techbriefs.com/tsp under the Physical Sciences category. LEW-18431-1

PLASTIC THERMOFORMING APPLICATIONS

Thermoforming is a process which uses heat and pressure and/or vacuum to form parts from an extruded (flat) sheet of thermoplastic. In the process depicted below (see Figure 5), plastic is drawn from large rolls, heated to its softening temperature, and then formed into a desired shape using an aluminum-forming tool. It is then cut into individual containers, stacked, inspected, counted, boxed and shipped. The heating section uses infrared heaters to soften the plastic sheet to forming temperature.

A group of thermoforming machine manufacturers and end-users identified that the electric energy cost to heat the plastic sheet accounts for 35% to 50% of the cost of the end product. The ability to use natural gas as the primary source of heating energy could reduce this number to less than 10% due to the 3:1 cost advantage of natural gas. The primary

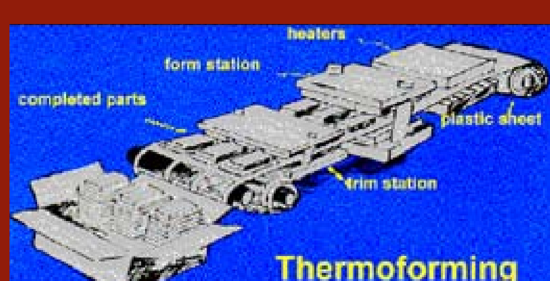
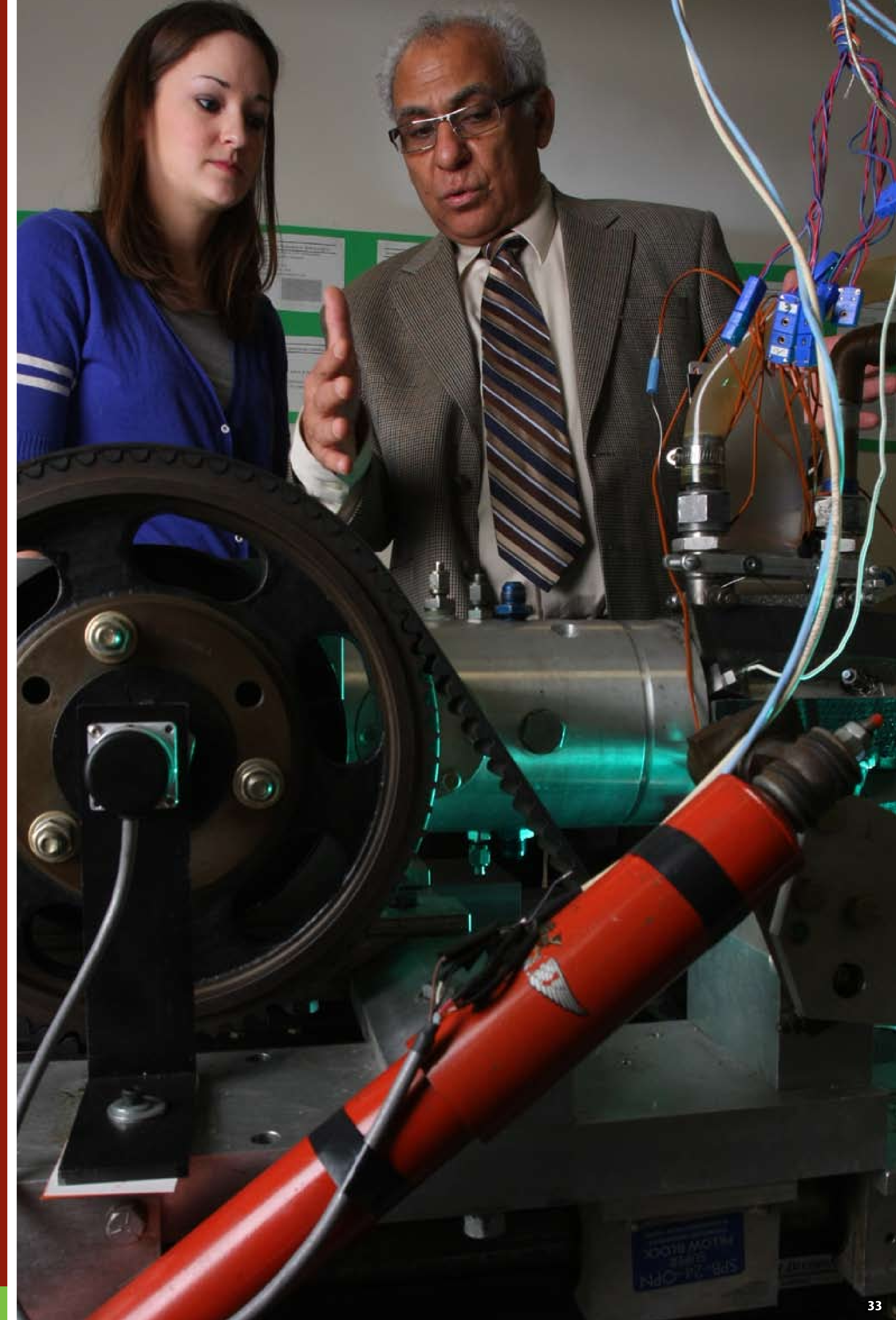


Figure 5: The Thermoforming Process

reason for not using gas-fired infrared was due to operating temperature and control limitations of available gas heaters. The optimum operating temperature of a heater used in the thermoforming process is 600º F to 1200º F. Gas catalytic heaters operate between 400º F to 950º F while gas ceramic heaters operate between 1400º F to 2000º F. Therefore, a gas fired infrared heater that operates between 600º F to 1200º F would offer the thermoforming industry a cost-effective product to reduce operating cost while maintaining part quality. A new gas burner was designed by Professor Ibrahim and Professor T. Briselden, Pennsylvania State University, (US patents #6368102 and #6612835) and 40 units were manufactured at CSU's Advanced Manufacturing Center under Professor Ibrahim's direction. This included Auto-CAD drawings, assembly drawing, material selections, burner individual testing, safety trains, and burner-panel assembly and operation. The project was supported by the Gas Technology Institute and by industry.

THERMAL ENERGY STORAGE SYSTEMS

Under support by NASA, Professor Ibrahim and his research group has been developing a computer code for analyzing the phenomena occurring in cylindrical metal canisters containing a high-temperature phase-change material. Such canisters are normally used as thermal storage elements in heat receivers of solar dynamic power systems for low-orbit space vehicles. The code is a useful canister design tool and able to predict the temperature distributions and the void behavior in the canisters. These in turn are used for the canister thermal stress analyses. The emphasis in the development of the code has been made on accurate descriptions of the solid-liquid phase change process, void dynamics and heat transfer, convective and radiative heat-transfer modes in the phase change material. The abilities of the code include computations of three-dimensional and axisymmetric heat transfer and fluid mechanics phenomena inside the canisters. The code validation has been made based on the results of ground tests and two thermal energy storage flight experiments. The validated code has been used for canister analyses. The following features have been examined: 1) the location of hot spots in the canister, especially canister walls; 2) the void location and heat-transfer predictions; 3) the importance of radiative and convective heat-transfer modes in the void and liquid phase change material; and 4) the influence of three-dimensional vs. axisymmetric boundary conditions on the canister performance.



Intelligent Systems for Engineering

Professor Lin's research has been funded by NASA to develop an intelligent system for monitoring the microgravity environment on-board the International Space Station and to develop a non-traditional technique to optimize the design of next generation's aircraft propulsion system.

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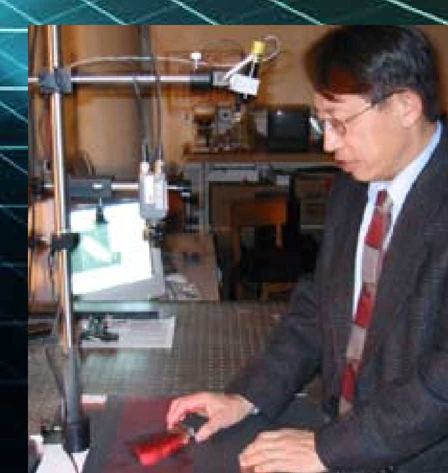
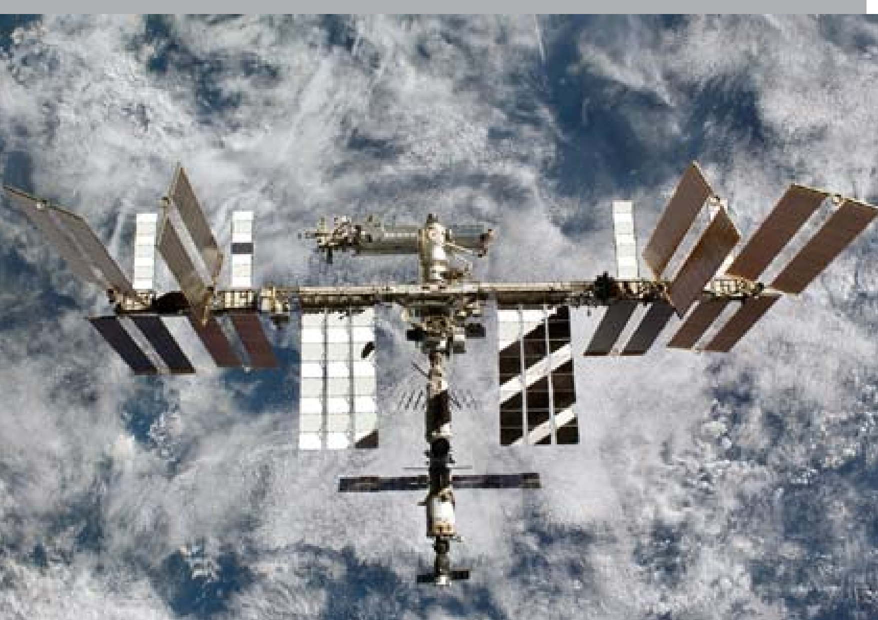
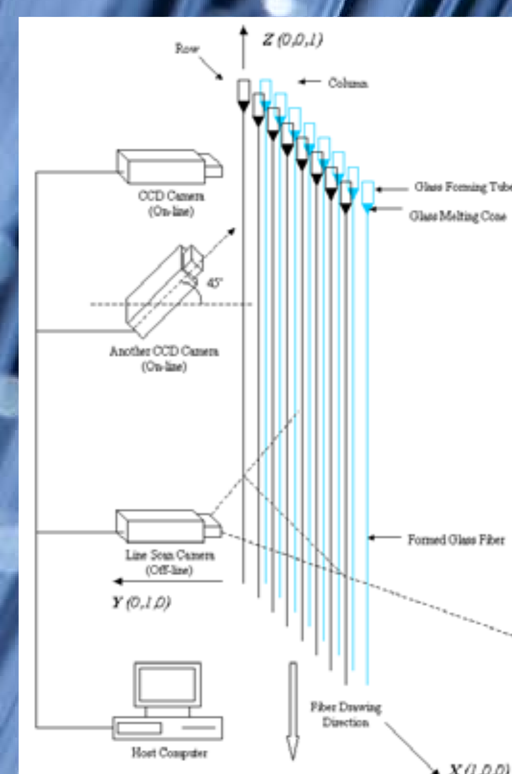


Professor Lin has 25 years of academic experience as faculty and administrative faculty in addition to three years of industrial experience as a machine designer and manufacturing engineer. He was elected to the grade of Fellow of the American Society of Mechanical Engineers in 2008 for his remarkable contributions in research and development. His areas of research expertise include Intelligent System Monitoring, Intelligent Fault Diagnosis and Self-Reconfiguration, Multi-Objective Optimization, and Machine Vision and 3-D Surface Measurement. More recently, Professor Lin received the 2009 Leadership Award from the Cleveland Engineering Society for recognition of his contribution to research and development, and involvements with local and national technical communities.





INTELLIGENT SYSTEM MONITORING

This three-year project was funded by the NASA Glenn Research Center to develop an intelligent system for monitoring the microgravity environment on-board the International Space Station (ISS). The developed computer program could automatically collect data from a satellite and perform Fast Fourier Transform (FFT) analysis as well as intelligent pattern classification and recognition. Relying on 14 three-dimensional accelerometers to collect acceleration amplitudes, the program could predict – with a high degree of confidence – what events had occurred, as well as how long and how strong their accelerations were. The predicted data was immediately posted to the ISS website for the earth-based principal investigators to view.

INTELLIGENT FAULT DIAGNOSIS AND SELF-RECONFIGURATION

Recently, Professor Lin developed intelligent fault diagnosis, prognosis and self-reconfiguration techniques for nonlinear dynamic systems. In terms of fault diagnosis, he developed new techniques using model-based approach and model-free approach. In the model-based approach, the concept of Extended State Observer (ESO) was successfully applied to fault diagnosis in the presence of modeling errors and disturbances. In the model-free approach, fuzzy logic and neural networks were used. More recently, Professor Lin successfully used α-β-γ Tracker technique for fault diagnosis. Prognosis and self-reconfiguration techniques were also developed. Professor Lin also participates in research with CSU's Center for Advanced Control Technology (CACT) which offers a unique control algorithm called Active Disturbance Rejection Control (ADRC) that can be used for self-reconfiguration.

MULTI-OBJECTIVE OPTIMIZATION

Professor Lin and his research group developed a non-traditional technique for the NASA Glenn Research Center to optimize the design for the next generation's aircraft propulsion system. There were 14 key parameters to be tuned in order to simultaneously maximize the thrust, minimize the fuel consumption, minimize the emission and minimize the jet velocity (noise). The optimization technique was not iteration-search based since the system model was not available. Instead, it relied on many sets of simulated input-output data. Conflict of interest was gracefully handled by means of fuzzy inference. With the use of soft computing, the compromised solution can always be reached by combined Taguchi analysis, neural networks and fuzzy logic.

In addition, Professor Lin and his research group have been active in the area of machine vision. He participated in a project funded by the Department of Energy through CSU's Advanced Manufacturing Center to develop a non-contact online glass fiber inspection technique. Glass fiber forming is a complicated process in which many factors could affect the quality of fibers. The forming machine has many fiber-forming tubes that are close to each other and arranged in several layers. The closeness results in inadequate lighting and unwanted signals. The fiber diameter measurements were performed online, and the entire inspection process was automated with the aid of a programmable logic controller.

Professor Lin developed a 3-D optical measurement technique called Fringe Projection using only one camera, and requiring no image superposition. Thus, it is simpler in hardware, and less sensitive to vibration.

He also developed a non-contact and dynamic measurement of aircraft tire deformation for the Wright-Patterson Air Force Base. Aircraft tires deform during landing, and improper landing angle could severely shorten the tire life. The tire deformation had been arbitrarily assumed in the Air Force's finite difference analysis until my optical measurement technique correctly quantified the deformation. As a result, the nationwide Aerospace Engineering Magazine introduced his technique as an innovative technology.

Professor Lin's activities extend outside the United States. He has established overseas collaborations to develop a system and methodology for online free form surface measurement via a fuzzy-logic controlled scanning probe. To improve the measuring stability and continuity, fuzzy logic control, in lieu of traditional PID control, was employed. The fuzzy logic controller exhibits the ability to handle uncertainty (i.e. abrupt surface variation).

Professor Lin's research has been recognized repeatedly nationally and internationally. In addition to his election as a Fellow of ASME, he was selected to participate in the first meeting of "NASA/NSF Research and Education Opportunities for Principal Investigators, Faculty and Partners" in 2007. He was a keynote speaker in an international conference, editorial board of two journals, Associate Editor in a IEEE/ASME conference, and a member of eight program committees. He was also elected as the coordinator of Dynamic Systems and Control Group (a group consisting of over 20 researchers in Ohio) in the Ohio Aerospace Institute in 1991-92 and his research work was featured in Akron's Beacon Journal in the late 1980's. Professor Lin has published more than 50 peer-reviewed articles.

Harnessing the Energy of Wind

In order to better harness the power of the wind, Professor Rashidi's research has focused on the potential of increasing the wind speed in areas with relatively lower speeds, where conventional windmills stay stagnant, using wind deflecting structures.

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This fully functional tower installed at Cleveland State University has an actively controlled system that orients the four turbines into the prevailing wind. The wind direction is determined with a small wind-speed-direction sensor apparatus. The wind direction data is then analyzed according to a control algorithm. The electricity generated by each turbine is conducted to a multi-channel junction box. Each turbine has its own inverter unit that transforms the generated power into AC power with adjusted phasing. The AC power is then fed into the Plant Services building of the University.

A NOVEL DESIGN BASED ON THE WIND SPEED AUGMENTATION PRINCIPLE

There is a better way to harness the power of the wind, especially at relatively lower wind speeds where conventional windmills stay stagnant. Professor Rashidi's research has focused on the potential of increasing the wind speed using wind deflecting structures. He envisioned a number of such structures that amplify the wind, from a spiral shaped system to one that resembles a silo. The focus is a cylindrical structure with rotating arms.

The new system is aligned with the US Department of Energy's initiative of Energy Efficiency and Renewable Energy, aimed to convert wind energy into electricity at places where the wind speed is relatively low. One of the goals is to reduce the cost of generating electricity by reducing the cost of a suitable structure that amplifies the wind speed. As the result of Professor Rashidi's design, the new system can be scaled up in a vertical direction, while keeping the footprint size and the size of its individual turbines the same for different targeted power ratings. Another unique feature of the design is its practicality and flexibility; it can, for example, be constructed and placed in farms with existing silo-shaped structures which can be retrofitted with his design.

Professor Rashidi is very interested in the commercial viability of his design as an alternative energy source. He is performing theoretical analysis to further optimize the design of the cylindrical structure, using computational fluid dynamics. A standalone, reference turbine, which is not affected by the wind amplifier structure, will be erected at various geographical sites, in the vicinity of Professor Rashidi's design, to help gauge and measure the difference in power capacity between traditional turbines and turbines on the cylindrical structure.

The new wind tower design has some unique features. One of them is that it can be used as a retrofit to existing cylindrical structures, such as water towers and silos. It is also applicable to urban areas with low wind speed (4 to 5 miles per hour). One of the main advantages of the new design is that it offers a significant increase in energy generation. Each turbine of the new design is able to produce an annual energy level equal to that produced by about 4 standard turbines under similar wind conditions.

Computational fluid dynamics simulation results (Figure 1) and preliminary experimental results both show that the new design reaches its maximum power generating capacity at a lower natural wind speed compared to the traditional design (turbine installed in a standard manner on a mast).

Experimental results from 2009 (Figure 2) show that turbines installed using the new design method (P1-P4) produced significantly higher amounts of energy compared to a turbine installed using the traditional method (P5).

Figure 1

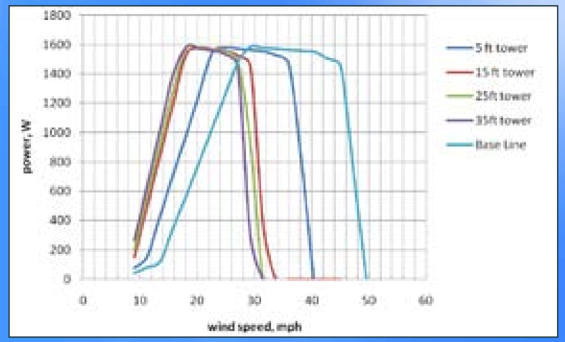
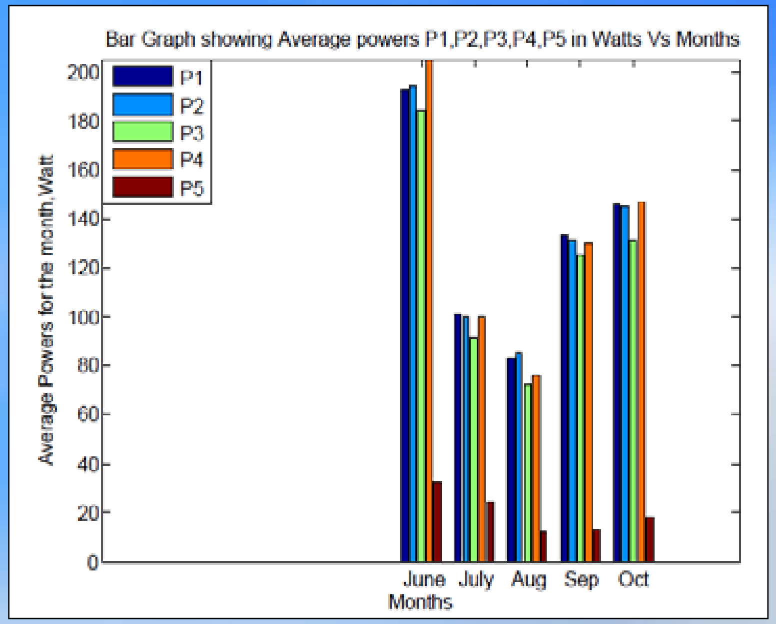
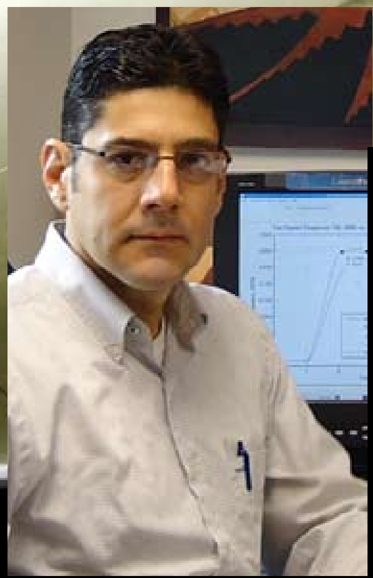


Figure 2





As the result of a long-standing research collaboration with NASA, Professor Richter has proposed and demonstrated advanced control strategies to ensure that critical variables do not exceed prescribed limits, a recurrent issue in aerospace control systems.

HANZ RICHTER

Ph.D., OKLAHOMA STATE UNIVERSITY

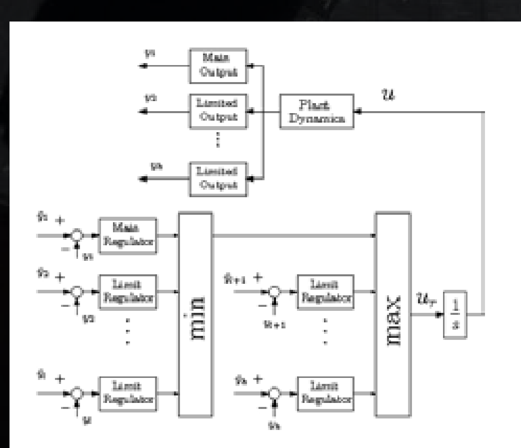
ASSOCIATE PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING

Professor Richter's research is concentrated in control systems theory and applications. He and his students also conduct research in the related area of mechatronic systems. He directs the Control Theory and Realizations Lab (CTRL). Research carried out at CTRL has resulted in numerous publications in high-visibility journals such as the *IEEE Transactions on Automatic Control*, the *AIAA Journal of Guidance*, *Dynamics and Control* and the *Journal of Intelligent Materials, Systems and Structures*, among others.

CONSTRAINED CONTROL SYSTEMS

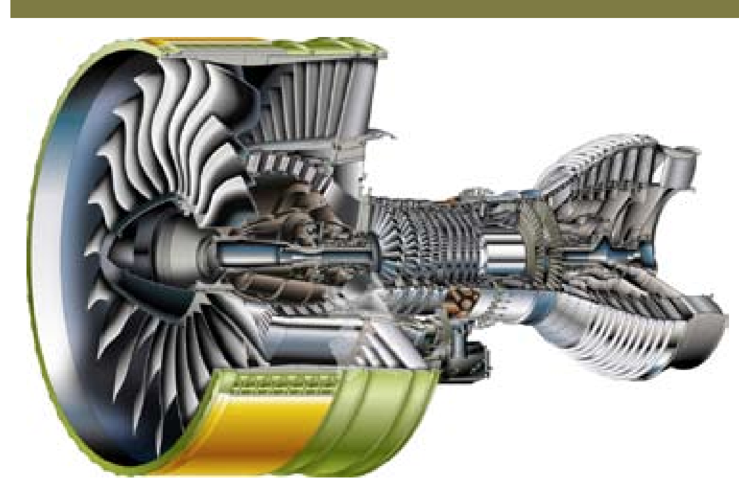
There is a large gap between the conceptual control system presented in textbooks and the actual real-time control implementation. The latter must account for various types of constraints, including permissible ranges for certain variables, limitations in the complexity and precision of real-time control calculations and limited availability of hardware associated with control channels. Professor Richter's research has addressed these constraints from the theoretical standpoint first, followed by applications to practical problems in a laboratory setting. Professor Richter points out that when a practical control implementation fails despite having followed the established theory, one should not disregard it, but rather revise it and expand it so that it accounts for the nuances associated with a real system.

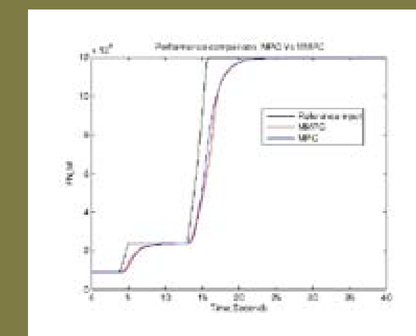
As the result of a long-standing research collaboration with NASA, Professor Richter has proposed and demonstrated advanced control strategies to ensure that critical variables do not exceed prescribed limits, a recurrent issue in aerospace control systems. In aircraft engines, for instance, the propulsion control system must provide fast response, while maintaining turbine temperature and stall margin within acceptable limits.

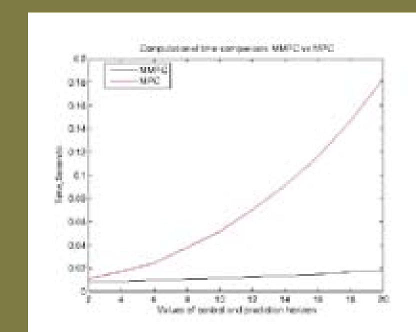


A multi-regulator sliding mode control scheme with max-min selectors was developed and successfully deployed to NASA's Commercial Modular Aero-Propulsion System Simulator (CMAPSS), a high-fidelity engine simulator used to validate control strategies. Although simulation studies alone provide strong evidence for the effectiveness of the proposed strategy, Professor Richter obtained a formal proof of stability and a complete characterization of system behavior.

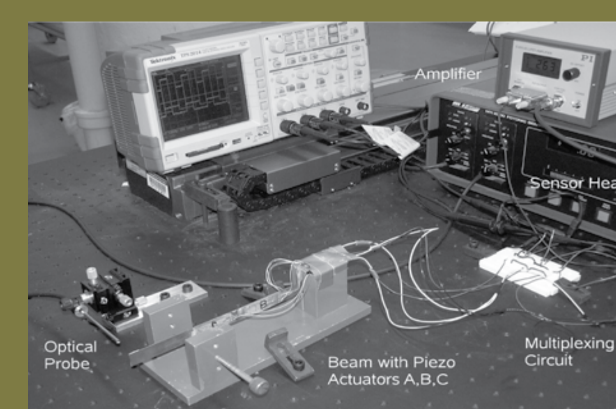
The problem of limited computational resources arises in aircraft propulsion control in conjunction with numerically-intensive control strategies such as Model-Predictive Control (MPC). In a NASA-funded project, Professor Richter proposed and developed a multiplexed model-predictive technique to stagger control-channel updates so that the quadratic program involved in MPC is solved for one actuator at a time, with considerable complexity reduction and substantial computation time savings. The results, published in the *AIAA Journal of Guidance, Dynamics and Control*, indicate that these savings do not incur serious performance degradation. These results improve the feasibility of MPC as a control paradigm for commercial aircraft engines.







A trade-off encountered in large-scale structural control problems is the need for enhanced controllability versus the implementation cost associated with a large number of control input channels. Motivated by the success of the multiplexed model-predictive control implementation for aircraft engines, Professor Richter applied his theory to the problem of stabilization of multi-degree-of-freedom smart structures using less power amplifier channels than actuators. The technique was demonstrated using a cantilever beam fitted with three piezoelectric actuators, of which only one was actuated at a time.



MECHATRONIC SYSTEMS

Professor Richter and his students are currently conducting exploratory research on an advanced algorithm for electromechanical power management applicable to hybrid electric bicycles. This project is being funded by CSU's Faculty Research Development fund. In this project, a prototype bicycle is being assembled which features an electrically-commanded, continuously-variable transmission and a front hub brushless motor. A salient feature of the envisioned system is the possibility of using the hub motor as an electric generator that charges the batteries by deriving kinetic energy from the bicycle, much like hybrid automobiles capable of regenerative braking. The optimizing algorithm will select the gear ratio which is more favorable according to the power usage model selected by the rider: "aggressive", "economy" or "assistive". In the first mode, the user receives little or no assistance from the hub motor and may even use pedal force to recharge the batteries as he rides. In the economy mode, the hub motor assists the rider if the speed falls below certain limit, and recharges the batteries only when the brakes are activated. In the assistive mode, energy conservation and regeneration receives low priority. These features will enhance the versatility of the bicycle both as a mode of transportation and as athletic training machine.

Also within the area of Mechatronic Systems, Professor Richter developed a biopolymer-based strain sensor using chitin, an organic polymer found in the shells of crustaceans. This material is known to exhibit piezoelectric properties, in addition to being bio-compatible. Due to its biocompatibility, chitin is used in the manufacture of surgical thread and wound dressings. In collaboration with Professor Paul Hambourger from the CSU Physics department, Professor Richter prepared a sensor prototype by vacuum-coating a thin film of biopolymer material with a layer of pure silver, forming electrodes. The sensor was successfully demonstrated by bonding it to a vibrating beam and measuring the strain. As a result of this work, Professor Richter was invited to be a US delegate to the US-Japan Symposium of Bio-Inspired Sensor Networks in Yokohama, where he presented his work.

Center for Rotating Machinery Dynamics and Control (RoMaDyC)

Professor Sawicki is the Director of the Center for Rotating Machinery Dynamics and Control (RoMaDyC) at Cleveland State University. RoMaDyC is dedicated to enhance productivity and competitiveness of its partners in industry. In association with industry, RoMaDyC focuses on problem solving and research to provide cutting-edge technical innovations in solving complex problems in engineering systems involving rotating machinery.

JERZY T. SAWICKI

Ph.D., CASE WESTERN RESERVE UNIVERSITY, P.E., ASME FELLOW

D.E. BENTLY AND A. MUSZYNSKA ENDOWED CHAIR AND PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING

INTERIM ASSOCIATE VICE PRESIDENT FOR RESEARCH, CLEVELAND STATE UNIVERSITY

Rotating machinery and their major components represent an important technology branch for the power generation, aircraft, chemical, petrochemical, and oil and gas industries, and for other major manufacturing industries. While this well-established engineering discipline has seen over 150 years of research and development, new engineering paradigms, designs, and materials can make possible significant improvements in machine system reliability and performance.

The Center for Rotating Machinery Dynamics and Control (RoMaDyC) is dedicated to enhance productivity and competitiveness of its partners in industry. In association with industry, RoMaDyC focuses on problem solving and research to provide cutting-edge technical innovations in solving complex problems in engineering systems involving rotating machinery. RoMaDyC serves as an intellectual resource for the industry with the aim of continuous improvement and long-term development. These activities directly support improvements in design, diagnostics, reliability, performance, durability, and environmental compliance of vital rotating mechanical systems and components. In addition to research and development, RoMaDyC maintains an active educational mission to both educate and provide information to the community regarding rotating machinery.

MAGNETIC BEARINGS RESEARCH

In the last decade, active magnetic bearings (AMBs) have come out of the laboratory and become established alternatives to high-performance bearings. Active magnetic bearings generate forces through magnetic fields. There is no contact between bearing and rotor, and this permits operation with no lubrication and no mechanical wear. A special advantage of these unique bearings is that the rotor-dynamics can be controlled actively through the bearings. As a consequence, these properties allow novel designs, high speeds with the possibility of active vibration control, high power density, operation with no mechanical wear, less maintenance and therefore lower costs.

MAGNETIC BEARINGS FOR HIGH-SPEED MACHINING

High speed machining is emerging as an important technique for achieving higher production rates, better surface finish, reduced forces and power, and production cycle times. To date, conventional ball bearing machine spindles can reach speeds in the range of 15-20K rpm at a maximum cutting power up to 30 kW. However, optimal cutting speed can most often not be reached using conventional spindles due to the limited surface speed of ball bearings.

Magnetic bearings have a high potential to replace rolling element bearings in high-precision high-speed machine spindles. To move the technique forward both in terms of higher rotational speeds and better dynamics of the cutting process, Professor Sawicki and his graduate students have been studying application of AMBs as the most feasible solution. Apart from the higher rotational speed, AMBs create possibility for on-line monitoring of the machining process (e.g., cutting force measurement, tool wear, tool deflection) which makes the AMB supported spindles very attractive for high-speed machining industry.

The study conducted in RoMaDyC has been concentrated on modeling of metal cutting dynamics and development of advanced control strategies for an AMB supported machine tool spindle (see Figure 1) towards the most optimal machining process. The experimental spindle is capable of running at 50,000 RPM and the achieved accuracy of the machined profile at the tool tip is in order of 0.5 μm. Model identification is essential for development of advanced controllers. Figure 2 shows comparison of the modeled and experimental open-loop transfer functions for the spindle.

High static stiffness at the cutting point is often considered the most desirable attribute of a machine tool spindle. It makes for high cutting accuracy and is sometimes used to give an indication of expected dynamic performance. The

Figure 1: AMB-supported high speed machining spindle.

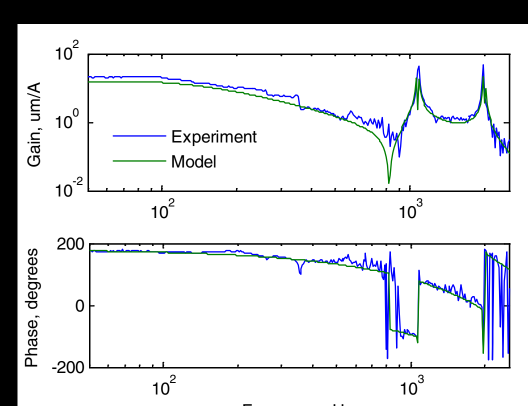


Figure 2: Modeled and experimental open loop transfer function for the AMB spindle.

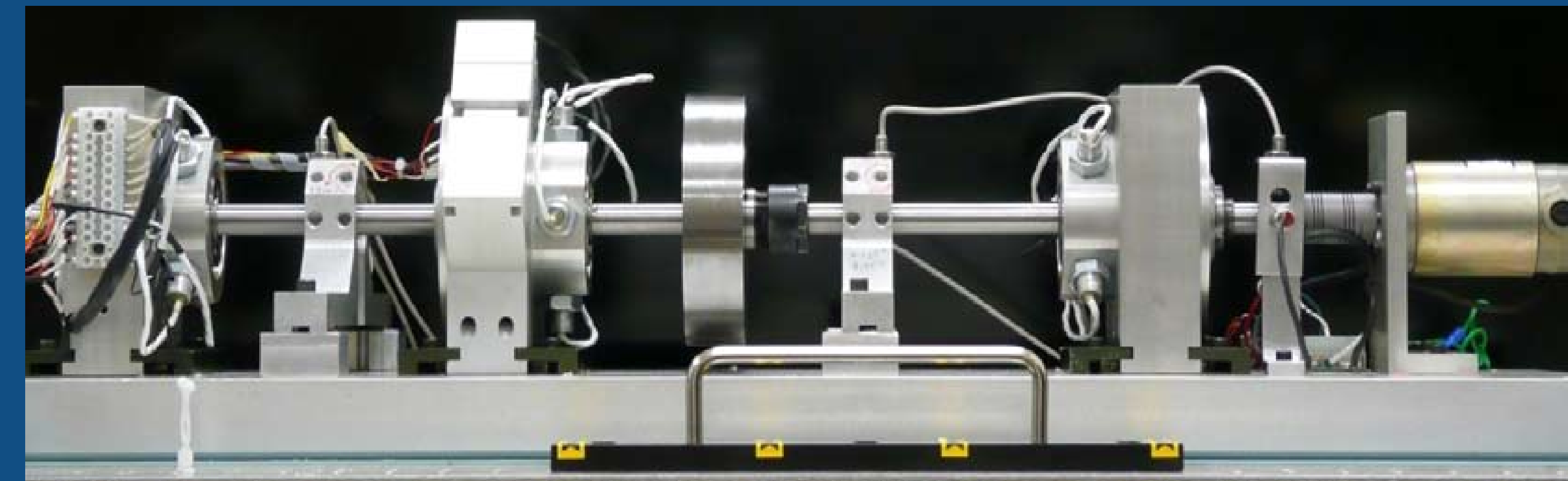


Figure 4: Experimental setup for online rotor crack detection with AMB force actuator.

dynamic flexibility (inverse of dynamic stiffness) at the cutting point indicates the susceptibility of a machine to chatter. Both stiffnesses depend upon several components in the tool-workpiece loop, although the spindle bearing system and control is of paramount importance. To determine the spindle stiffness at the tool tip, with the rotor supported on each of the three controllers, PID, μ-controller, and optimized μ-controller, impact testing was carried out with an instrumented hammer. The results presented in Figure 3 show the advantage of MIMO (Multi Input Multi Output) controllers, especially in the vicinity of the first and second modes, where PID stiffness is significantly lower.

STRUCTURAL HEALTH MONITORING FOR POWER GENERATION AND PROPULSION SYSTEMS

The increasing requirements for high performance, safe operation, and long component operational life call for the development of accurate and reliable machine health monitoring systems capable of providing on-line diagnosis of rotating machinery conditions, and machine life prognosis, including advance warning of component failure. Of all machine faults, probably cracks in the rotor pose the greatest danger and research in crack detection has been ongoing for the past several decades. Current methods examine the response of the machine to unbalance excitation during run-up, run down or during normal operation, and most often they are not reliable.

ACTIVE STRUCTURAL HEALTH MONITORING

It is not an easy task to distinguish a cracked (damaged) rotor from a healthy one. To overcome this deficiency, Professor Sawicki and his team explores application of active magnetic bearing as an actuator using specially designed experimental rotor test rig shown in Figure 4. To approximate the effect of a crack, a notch is cut using technique known as wire Electrical Discharge Machining (EDM) with the very small wire diameter (1.143×10^{-4}m). The notch is located on the shaft between the magnetic actuator and the large unbalance disk. The excitation waveform for the magnetic actuator, positioned near the unbalance disk, is generated in MATLAB/SIMULINK environment and transferred to hardware using a dSPACE DS 1103 board.

If the force excitation is injected to the rotating rotor, then the presence of a crack, acting as a strong nonlinearity in the system, can generate responses containing additional frequencies that are rational combinations of the rotor spin speed, critical speed and applied forcing frequency. These additional frequencies may be used as the signature of a

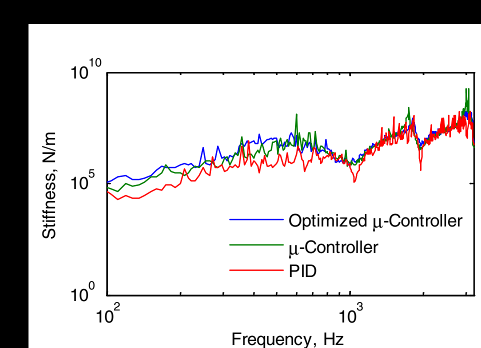


Figure 3: Experimentally extracted spindle stiffness at the tool tip for PID and μ-controllers.

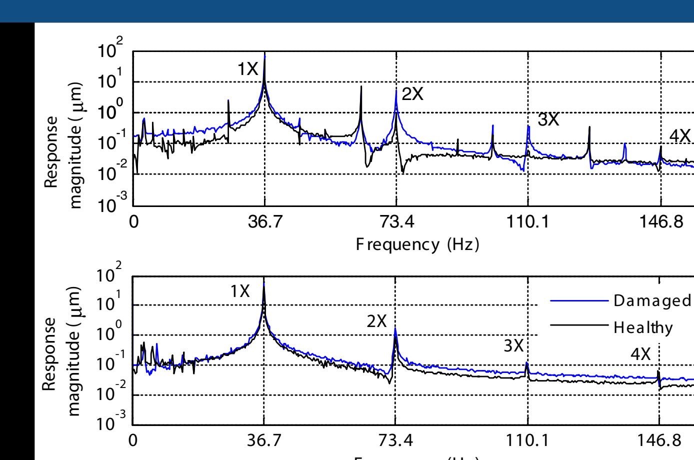


Figure 5: Measured response magnitude of rotor vibrations versus frequency for healthy and damaged rotors (top) and with (bottom) external excitation. Rotational frequency is 36.7 Hz, magnetic actuator frequency is 63 Hz.

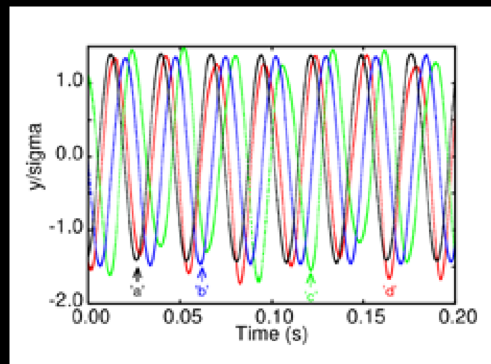


Figure 6: Experimental time series of the healthy ('a' & 'c') damaged ('b' & 'd') machine for a spin velocity 36.7 Hz: ('a','b') without external excitation; ('c','d') with magnetic actuator frequency 63 Hz.

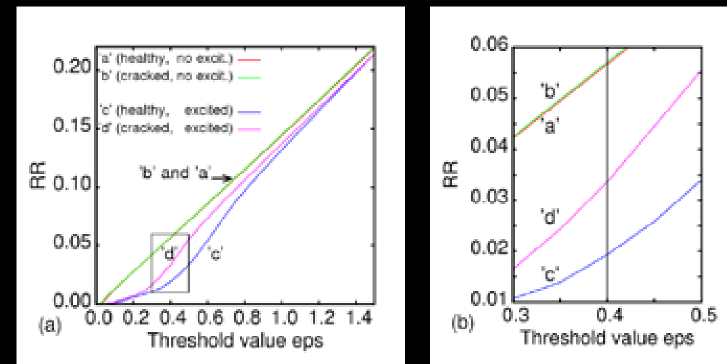


Figure 7: Recurrence rate versus the threshold value (eps) for the healthy and damaged rotors (cases 'a'-'d' as in Figure 6).

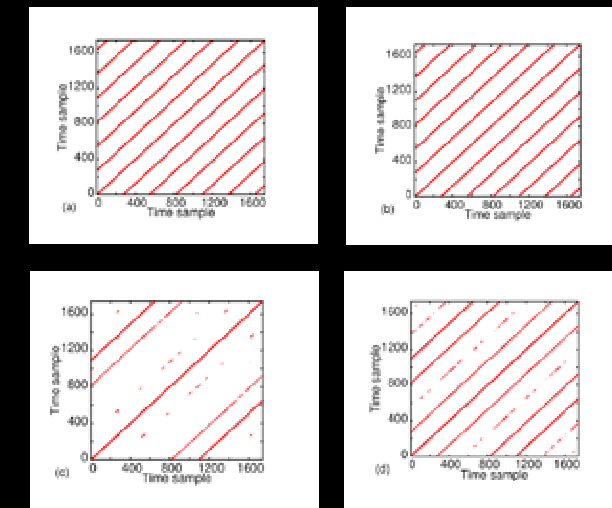


Figure 8: Recurrence plots of the damaged and healthy rotor for a spin velocity 36.7 Hz. Cases 'a'–'d' correspond to the corresponding time series presented in Figure 6: (a,b) without and (c,d) with magnetic actuator frequency 63 Hz.

crack and thus may be used for crack detection and identification. The top of Figure 5 shows the measured machine response with the damaged (notched) and healthy rotor due to the residual unbalance. The response is characterized by a major peak at the synchronous frequency of 36.7 Hz. The integer multiple harmonics of the spin speed (2X, 3X, . . .) can also be seen in the response but their magnitude is very small compared to the synchronous 1X frequency component (note the logarithmic scale). It is noticeable that the response magnitude is higher almost at all frequencies for the damaged machine. The bottom of Figure 5 compares the measured rotor response of the machine with the damaged (notched) and healthy rotor due to the residual unbalance and the externally applied magnetic force excitation having the frequency of 63 Hz and amplitude of 20 N. The rotor spin speed, its harmonics (1X, 2X, 3X, . . .) and the actuator frequency of 63 Hz can be noted in the response. In addition, there are visible peaks of combination resonances at 26.3, 63, 83.6, 99.7, 120.3 and 136.3 Hz. The pattern of induced resonances presents a unique crack signature and has potential to produce a robust condition monitoring technique.

APPLICATION OF NONLINEAR ANALYSIS AND DYNAMICS TOOLS

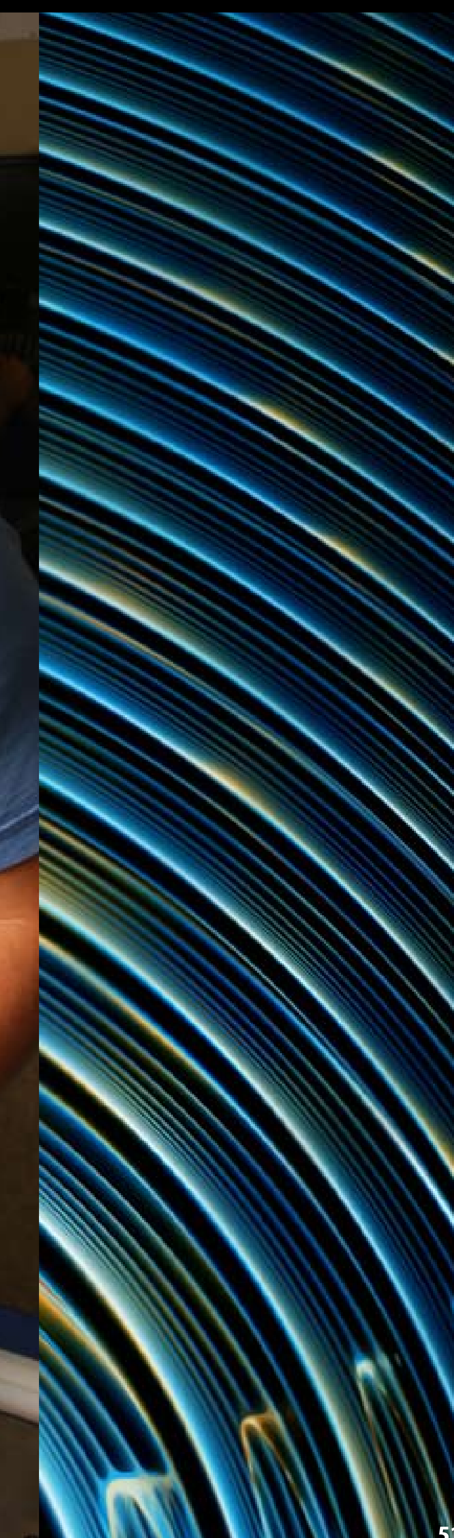
Professor Sawicki's research team applies novel nonlinear analysis and nonlinear dynamics methods for detection of structural damage in rotating structures.

Application of recurrence plots (RPs) analysis allows considering the state of a dynamical system using time versus time diagrams instead of doing Fourier analysis. Recurrence plots are special graphical tools designed to analyze experimental time series and detect hidden dynamical patterns and nonlinearities in the data. The examples of time series for the healthy and cracked rotor responses (the same as shown in Figure 5), without and with AMB excitation, are presented in Figure 6.

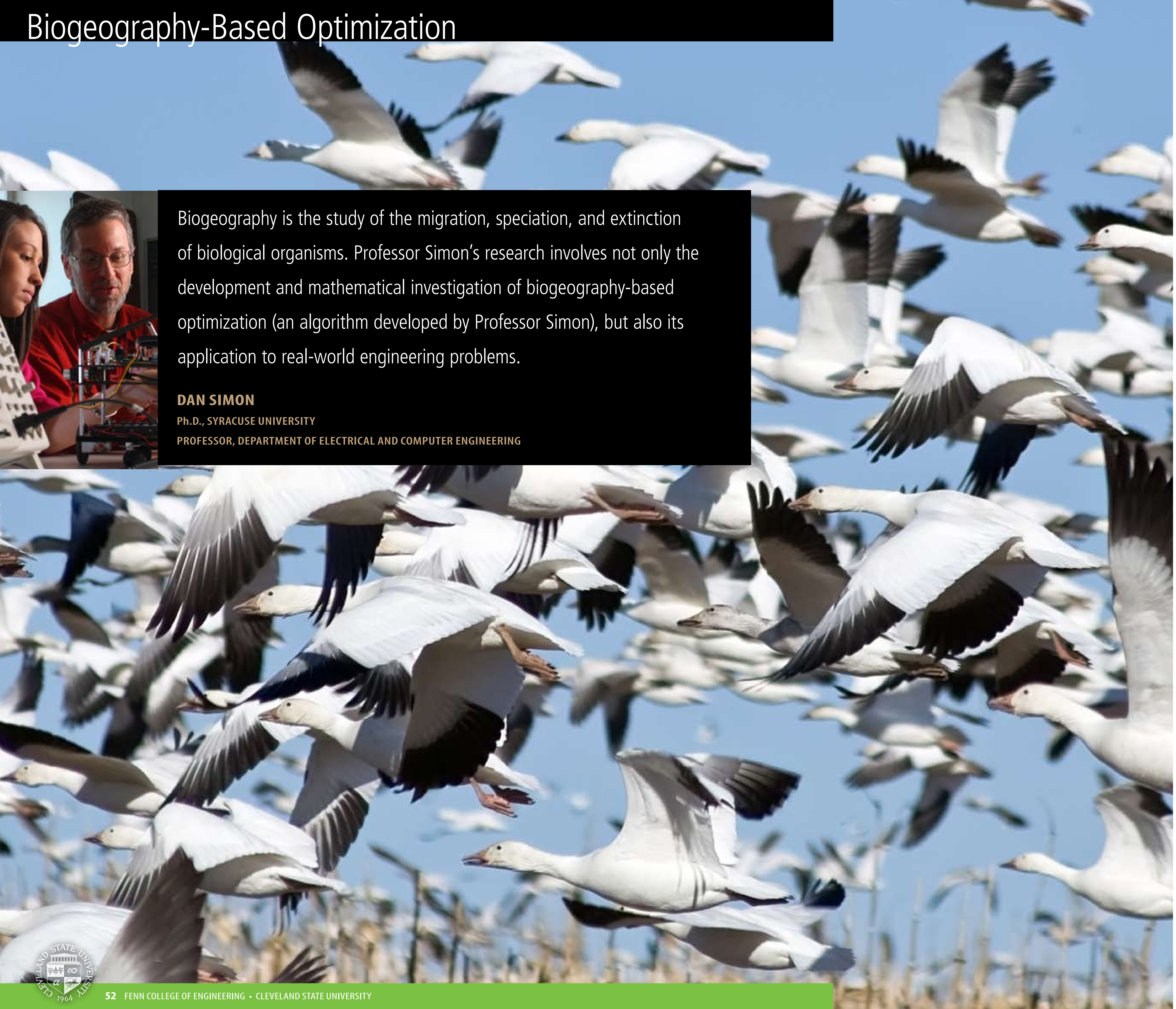
The recurrence rate (RR) expresses the measure of system regularity in nonlinear dynamical system. The plot of RR versus the threshold value eps (ε), for all four time series data shown in Figure 6, is presented in Figure 7. Here, one can observe in Figure 7(a) characteristic line splitting effect visible for $\varepsilon \in [0.3, 0.7]$. This effect can be noticed only in the presence of magnetic excitation (curves 'd' and 'c' are split) while for non-excited cases is negligible ('a' and 'b' coincide). Two conclusions can be drawn, first that the regularity of healthy and cracked rotor responses represented by the parameter RR is very similar for the cases without magnetic excitation, and second, that this regularity is considerably changed in the presence of magnetic actuators, i.e., cracked rotor shows more regular response than the healthy system. This could be also interpreted that the response is more periodic as a result of extra coupling by breathing action of the crack, and consequently, the response of the cracked rotor excited by an AMB should contain combinational resonances.

To clarify the origin of the splitting, the corresponding recurrence plots are shown in Figures 8(a)-(d), where the recurrences are illustrated for the threshold value (eps) set to 0.4. Note that Figures 8(a)-(b) (no magnetic excitation) show rather periodic character while this periodicity is smeared considerably in Figures 8(c)-(d) (with magnetic excitation). Clearly, among the all four cases, the case in Figure 8(c) is the most affected by the magnetic force excitation, which indicates that the presence of crack recovers partially the original periodic character of the basic response.

Currently, Professor Sawicki's research team works to extract information about the location and severity of the crack, which is contained in the amplitude of the response at combination frequencies. Thus, to establish the condition of the machine, the inverse problem must be solved, and the efforts are made to investigate model based inverse methods based on a range of processed measured data and to optimize the form and frequency of the external excitation to improve the conditioning of the estimation process.



Biogeography-Based Optimization



Biogeography is the study of the migration, speciation, and extinction of biological organisms. Professor Simon's research involves not only the development and mathematical investigation of biogeography-based optimization (an algorithm developed by Professor Simon), but also its application to real-world engineering problems.

DAN SIMON
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BIOGEOGRAPHY-BASED OPTIMIZATION: SIMULATING MIGRATION TO SOLVE ENGINEERING PROBLEMS

Biogeography is the study of the migration, speciation, and extinction of biological organisms. Biogeography-based optimization (BBO), an algorithm which has recently been developed by Professor Simon, is based on the science of biogeography. BBO represents problem solutions as islands, and represents the sharing of features between solutions as migration between islands. A computer simulation of the mathematics of species migration allows us to solve real-world engineering problems.

Mathematical models of biogeography describe the migration, speciation, and extinction of species. Biogeography began with studies in the 19th century, most notably by Alfred Wallace and Charles Darwin. Mathematical models of biogeography were introduced by Eugene Munroe in 1948. The work of Robert MacArthur and Edward Wilson in the 1960s was instrumental to the development and popularization of mathematical biogeography. A fascinating account of biogeography for the educated layperson was written by science writer David Quammen in his text "The Song of the Dodo: Island Biogeography in an Age of Extinction."

Islands that are suitable as habitats for biological species support many species. Island characteristics that correlate with habitability include features such as rainfall levels, topographic diversity, land area, and temperature. Highly habitable islands tend to have a large number of species because of the islands' friendliness to life; islands with a low level of habitability tend to have a small number of species because of their hostility to life. Islands with large populations usually have many species that emigrate to nearby islands because of the accumulation of random effects. Emigration occurs as animals ride flotsam, fly, or swim to neighboring islands. However, islands with large populations usually have only a few immigrants. This is in spite of their high suitability for life; an island with many inhabitants is often unable to support additional species, so immigration is low.

Islands with small populations usually receive many immigrants from other islands. This is because an island with a small population has room for many additional species. Whether or not those immigrating species can survive in their new home is a different question, but the immigration of species to sparsely populated islands may improve the suitability of those islands for life, because habitability is positively correlated with biological diversity.

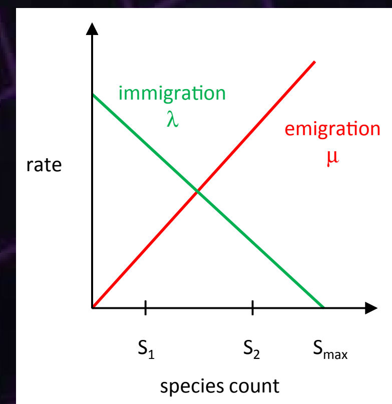


Figure 1: Illustration of how migration rates vary with the number of species on an island.

Figure 1 illustrates how migration rates vary with the number of species on an island. An island with S_1 species is sparsely populated and thus has a high immigration rate and a low emigration rate. An island with S_2 species is densely populated and thus has a low immigration rate and a high emigration rate.

As species migrate between islands, not only are the species benefited by finding a new home, but the islands become more habitable for future immigrations. A dramatic example of this process is Krakatoa, a volcanic island in the Indian Ocean which erupted in August 1883. The eruption was heard from thousands of miles away and resulted in the death of over 36,000 people, mostly from tidal waves whose remnants were recorded as far away as England. The eruption threw dust particles 30 miles high which remained aloft for months and were visible all around the world. The first visitor after the eruption, a geologist and mining engineer, arrived at the island six weeks after the eruption, but the surface of the island was too hot to touch and showed no evidence of life. The island was completely sterilized. The first animal life, a spider, was discovered on Krakatoa in May 1884, nine months after the eruption. By 1887, dense fields of grass were discovered on the island. By 1906, plant and animal life was abundant. Although volcanic activity continues today on Krakatoa, by 1983 (one century after its desolation) there were 88 species of trees and 53 species of shrubs on the island, and the species count continues to increase linearly with time.

Life immigrates to Krakatoa, and immigration makes the island more habitable, which in turn makes the island friendlier to additional immigration. One can see that biogeography is a positive feedback phenomenon. This is analogous to natural selection, also called survival of the fittest. As species become more fit, they are more likely to survive. As they continue to survive, they are better able to adapt to their environment and thus become more fit. Natural selection, like biogeography, entails positive feedback. However, biogeography is an optimization process that occurs on a time scale that is much shorter than natural selection.

FROM BIOGEOGRAPHY TO OPTIMIZATION

Engineers often look to nature for inspiration and motivation. Biogeography-based optimization (BBO) was first published by Professor Simon in 2008 as an example of how a natural process can be simulated in a computer to solve engineering problems. This is similar to what has occurred in the past few decades with other processes. For example, genetic algorithms model natural selection; artificial immune systems model biological antigens and antibodies; simulated annealing models the cooling process in crystals; and particle swarm optimization models the behavior of insect swarms. All of these algorithms are based on natural processes which have been adapted to solve engineering problems.

The design of a BBO algorithm begins with an arbitrary problem and several candidate solutions. The set of candidate solutions is called the population. As the candidate solutions are evaluated, some of them appear to be better than others. A good solution can be compared to a habitable island, and a poor solution can be compared to an inhabitable island. Good solutions are likely to share their features with other solutions, just like habitable islands which have high emigration rates. Poor solutions are likely to accept shared features from other solutions, just like inhabitable islands which have high immigration rates.

In biogeography, species migrate between islands. However, in BBO, solution features migrate between solutions. The migration probabilities are based on curves similar to those shown in Figure 1. S_1 represents a poor solution to a problem, and S_2 represents a good solution to a problem. Figure 1 shows that S_1 is likely to receive features from other solutions, while S_2 is likely to share features with other solutions. The BBO algorithm can be summarized as shown in Figure 2. One execution of the logic shown in Figure 2 is referred to as a generation. As the algorithm executes for many generations, the solutions gradually improve as they share information with each other.

Professor Simon's research involves not only the development and mathematical investigation of BBO, but also its application to real-world engineering problems. Several examples are discussed below.

POWER GENERATION

A power utility company often owns several different types of generating plants. These could include coal, natural gas, nuclear, and hydroelectric. The power generation cost and the pollution emissions depend on the type of the plant. Demand for power changes with location, time of day, and season of the year. Utilities try to adjust power output levels to achieve the minimum possible operating costs and to meet three constraints. The first constraint is that the emissions must not exceed that which is allowed by law. The second constraint is that the power and voltage levels at each electrical connection in the system must be maintained within certain limits for efficiency, equipment protection, and safety. The third constraint is that the power generated by the plant must equal the sum of the power consumed by the loads and the power losses that occur in the transmission system. Although this constraint is automatically satisfied in a real system due to the law of the conservation of energy, it needs to be incorporated in a plant's power generation algorithm in order to obtain a distribution scheme that is physically feasible.

The problem of calculating voltages in a power distribution system that satisfies the law of the conservation of energy is known as the power flow problem. The power flow problem can be solved by BBO. Each individual in the BBO algorithm represents a particular set of voltages in the power distribution system. In the BBO algorithm, an initial population of individuals is randomly generated. The mismatches between the generated and absorbed powers are then calculated for each BBO individual, and a cost is assigned on that basis. The BBO individuals share information (voltages) with each other based on the migration strategy of Figure 2.

```
For each solution H_i
  For each solution feature s
    Select solution H_i with probability λ_i
    If solution H_i is selected then
      Select H_j with probability μ_j
      If H_j is selected then
        Set H_i(s) equal to H_j(s)
      end
    end
  next solution feature
next solution
```

Figure 2: One generation of the BBO algorithm.

Ideally, one wants the cost to be zero, which indicates that the law of conservation of energy is perfectly satisfied by the given power distribution scheme. The goal of the BBO algorithm is therefore to find a set of voltages which give a mismatch that is close to zero. Professor Simon implemented a BBO algorithm for a power system with 30 connections between the generating plant and its electrical loads. The performance of the algorithm is shown in Figure 3, which illustrates that BBO is able to find a good solution to the power flow problem.

CARDIAC DISEASE DIAGNOSIS

Cardiovascular disease is the major cause of death in the western world; it results in over 800,000 deaths per year in the United States alone. About 20% of Americans have some form of cardiovascular disease. Cardiomyopathy is a cardiovascular disease which involves the enlargement or thickening of the heart muscle. Changes to the heart muscle affect the electrical stability of the heart cells, and this predisposes the heart to failure. Cardiomyopathy can be seen in changes of electrocardiogram (ECG) characteristics.

Professor Simon designed a decision network to extract carefully chosen features from an ECG and thus diagnose cardiomyopathy. He used BBO to find the best parameters of the decision network. He collected a database of ECG signals from patients at a local hospital. The database includes ECG signals from 55 subjects, 18 of them with cardiomyopathy and 37 of them without. He further divided the patients into two groups: a training group and a test group. BBO used the training group to find the best parameters for the decision network. Then he used the test group to see if the resulting decision network could accurately diagnose cardiomyopathy.

Figure 4 shows the BBO training results. The results show a correct classification rate on the test data of over 60%. Better results can undoubtedly be attained with additional work, but the main goal of this initial research was to demonstrate feasibility.

EVOLUTIONARY ROBOTICS

In order to demonstrate that BBO can optimize a physical engineering system, Professor Simon trained the control algorithms of microprocessor-based mobile robots to enable the robots to perform a tracking task as accurately as possible. He used six robots (see photo on right), each equipped with ultrasonic sensors that allow them to detect how far they are from a wall. The robots' goal is to follow the wall with as little variation as possible. As the robots follow the wall, they upload their tracking data over a wireless radio link to a desktop computer, where the BBO algorithm is programmed. Each robot has a different set of control parameters and therefore represents a different solution to the control problem. The computer adjusts each robot's control parameters based on the BBO algorithm. After BBO calculates new control parameters, the computer radios that information to the robots, which repeat their tracking task. This represents one generation of the BBO algorithm.

Figure 5 shows how BBO can optimize the control algorithm of a robot. Professor Simon started the BBO algorithm by randomly generating tuning parameters for the controllers. The top graph in Figure 5 shows that the controllers are far from optimal. The robot eventually reaches the desired distance from the wall, but not before a lot of oscillations. The bottom graph in Figure 5 shows that the robot control performance is much more stable and steady after BBO controller tuning than before.

This work was supported by the CSU Provost's Office, the College of Engineering, the Department of Electrical and Computer Engineering, and the National Science Foundation. The work was conducted in collaboration with CSU students Dawei Du, Mehmet Ergezer, Rick Rarick, George Thomas, Rob Morabito, and Pavel Lozovyy, and CCF research associate Mirela Ovreiu, who received her doctoral degree from CSU. Additional details about this work, including BBO code and technical papers, can be found at http://academic.csuohio.edu/simond.

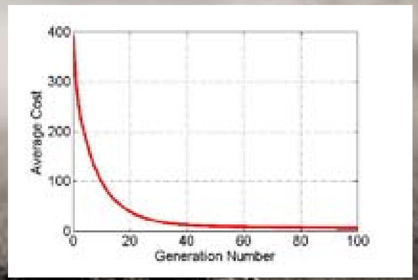


Figure 3: The evolution of BBO solutions to the power flow problem.

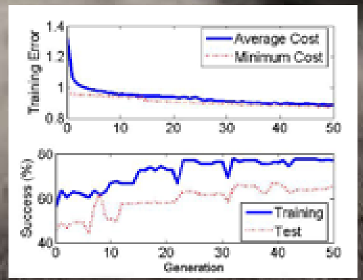


Figure 4: BBO training results for heart disease diagnosis.

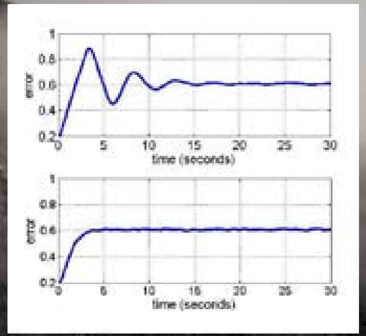
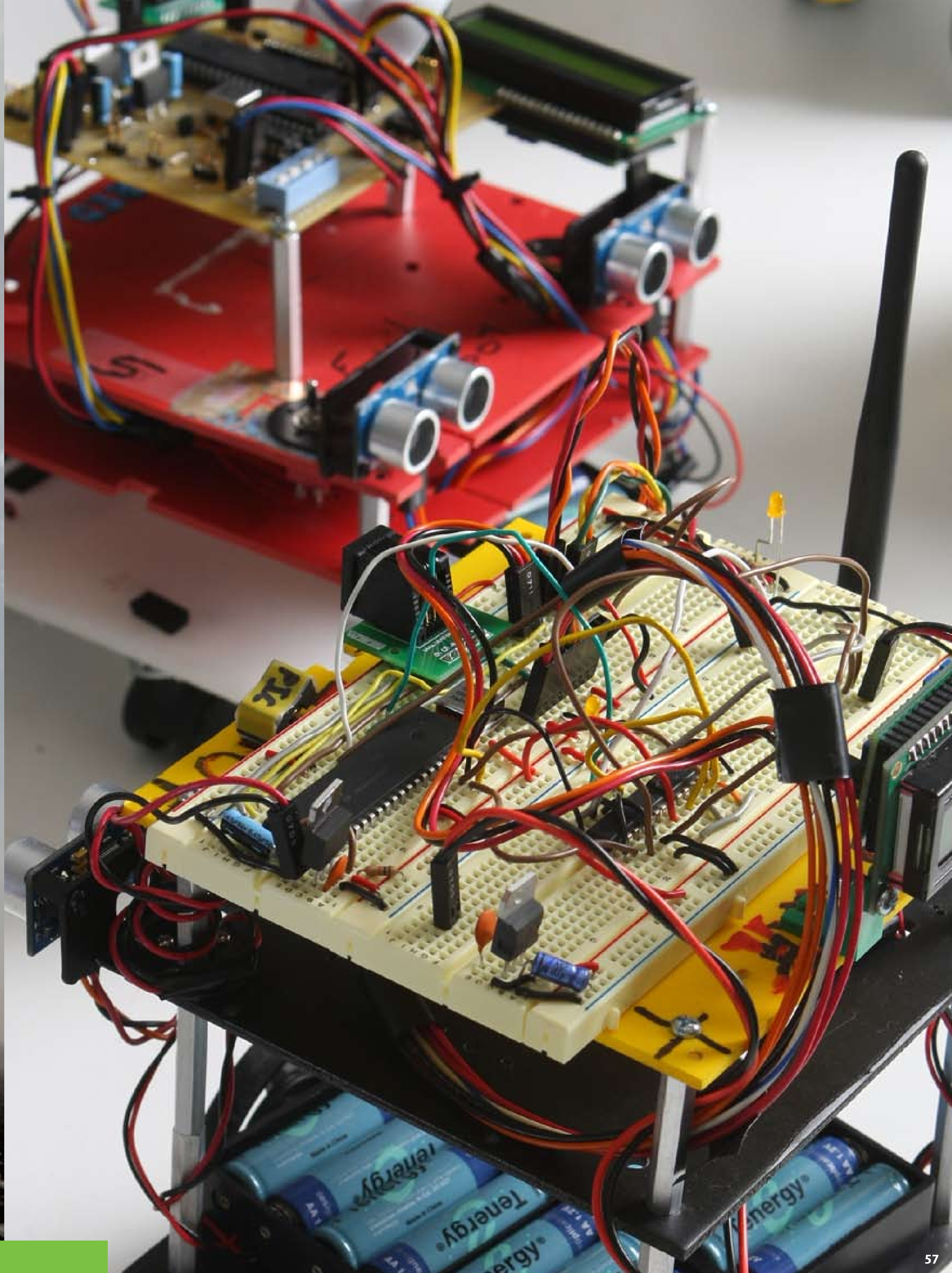


Figure 5: Microcontroller based robot with camera and ultrasonic sensors



The true potential of wireless sensor networks or sensornets can only be realized if the technology is mature and robust enough that researchers and scientists outside the computing disciplines can conceptualize, develop, and deploy sensornets themselves. The central theme of Professor Sridhar's research is to investigate the appropriate technologies that will help realize this vision.

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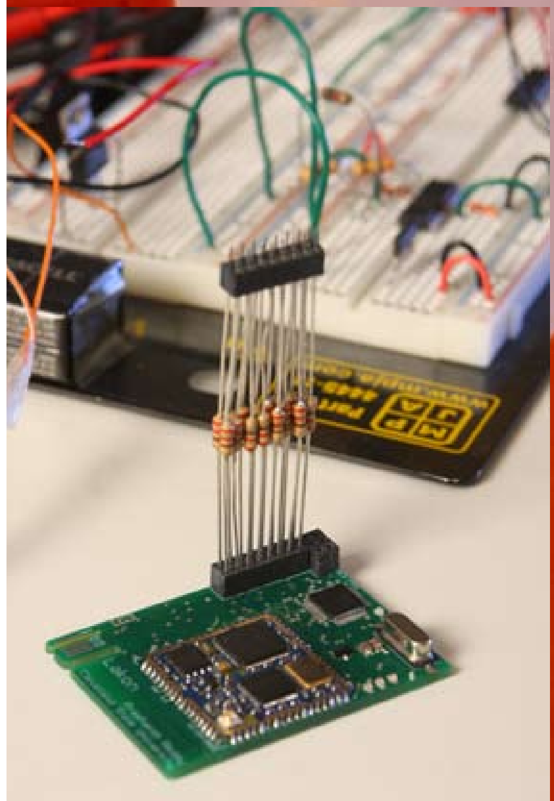
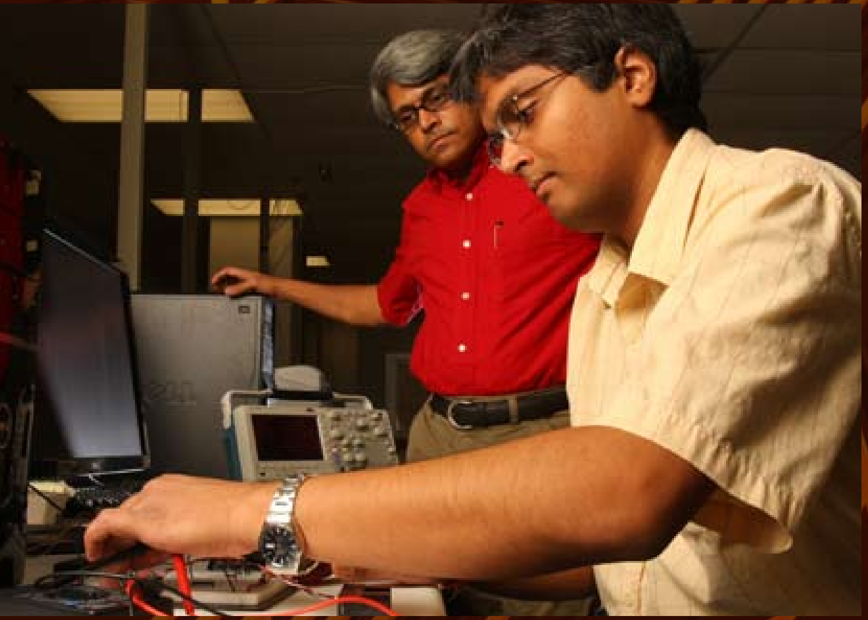


Over the past decade or so, wireless sensor networks (sensornets) have emerged as a key enabling technology to achieve fine-grained observation and control of the physical world that we live in. Advances in the area of developing small and inexpensive devices capable of capturing sensory input, and processing such input, have provided a rich set of technologies and platforms for use in building large-scale sensornets. Along with the development of these hardware platforms, the research community has also been actively engaged in developing protocols and algorithms aimed at combating the challenges presented by the extremes that are a consequence of the hardware being small and inexpensive — high rate of failure, limited resources, very large numbers — to name a few. In addition, the community has produced a number of competing software platforms for programming sensornet applications.

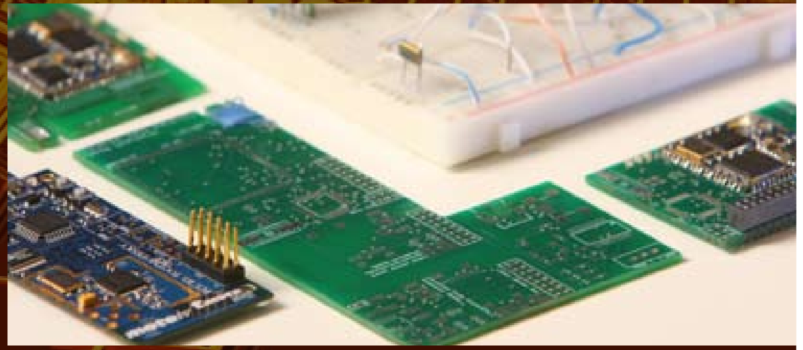
In spite of all these advances, large-scale networks of sensors are incredibly hard to build. The time and effort required to build software for such systems are not proportional to the size of the software itself: most of these applications are only a few hundreds of lines of source code, but take a disproportionate amount of time (several weeks, even months) to develop. The primary reason for this is immaturity of current state of the technology available for programming sensor network applications. Almost every major deployment of sensornets has included a team of computer science researchers to serve as programmers. This is a sub-optimal situation. The true potential of sensornets can only be realized if the technology is mature and robust enough that researchers and scientists outside the computing disciplines can conceptualize, develop, and deploy sensornets themselves. The central theme of Professor Sridhar's research program is to investigate the appropriate technologies that will help realize this vision.



By their nature, wireless sensor networks can provide a previously unimaginable reach for scientists and researchers who deal with physically occurring phenomena. Take for example, a human factors researcher studying traffic flow patterns in highway work zones, and in particular studying why the rate of crashes is higher than average in work zones. The work zone can be instrumented with a large number of networked sensors that collect data about vehicles moving through the work zone. The data could include rate of vehicle traffic, speeds of individual vehicles, steadiness of vehicle trajectories, rates of speed changes (e.g., sudden vs. gradual), etc. Using such data collected over a prolonged period of time, the researcher can piece together the collective behavior of a large number of drivers traveling through work zones. Contrast this with more "traditional" ways of conducting such research: by way of surveys of drivers (limited by the accuracy of their memories), or by way of video footage acquired from cameras monitoring the region (limited by the field of view and granularity of the cameras).

There is a fundamental roadblock here, however. The human factors researcher who is interested in conducting this research is not trained in programming in languages such as C, or using event-based programming paradigms that pervade the state-of-the-art in sensor network programming, or functional programming languages, or database views of sensor networks. So she likely turns to find a collaborator in computer science that can help with assembling the network and writing the software for collecting and processing the interesting data. This collaboration is nice: there is scope for new research in the computer science side of the project as well. In the long run, however, it is more optimal if the human factors researcher were able to deploy and program the sensornet herself. The domain knowledge she possesses can manifest in the software much better, and she would be able to make changes to the software easily to tweak the kinds of data coming out of the network to better suit the science.

This is the central goal of Professor Sridhar's research: making programming networked embedded systems such as wireless sensor networks accessible to practitioners and "non-programmer specialists." Professor Sridhar and his research group are on their way to realizing this goal by way of a number of projects, including the following samples of their newest work.



WIRELESS SENSOR NETWORKS IN CONSTRUCTION WORK ZONES *through the Cleveland State University Transportation Center of which Professor Sridhar is the Associate Director for Research*

Short-term duration work zones present a unique problem with respect to monitoring traffic. The work zones are hazardous areas, and therefore merit active monitoring of traffic and driver behavior. Yet, the state-of-the-art in monitoring equipment and technology is too cost-prohibitive for use in work zones that last only a few hours. In collaboration with Area Wide Protective, Inc., the Cleveland State University Transportation Center has been looking at this problem of developing cost-effective solutions to this problem. The work thus far has focused on the technology behind building a distributed networked instrument for measuring traffic flowing through a short-term duration work zone.

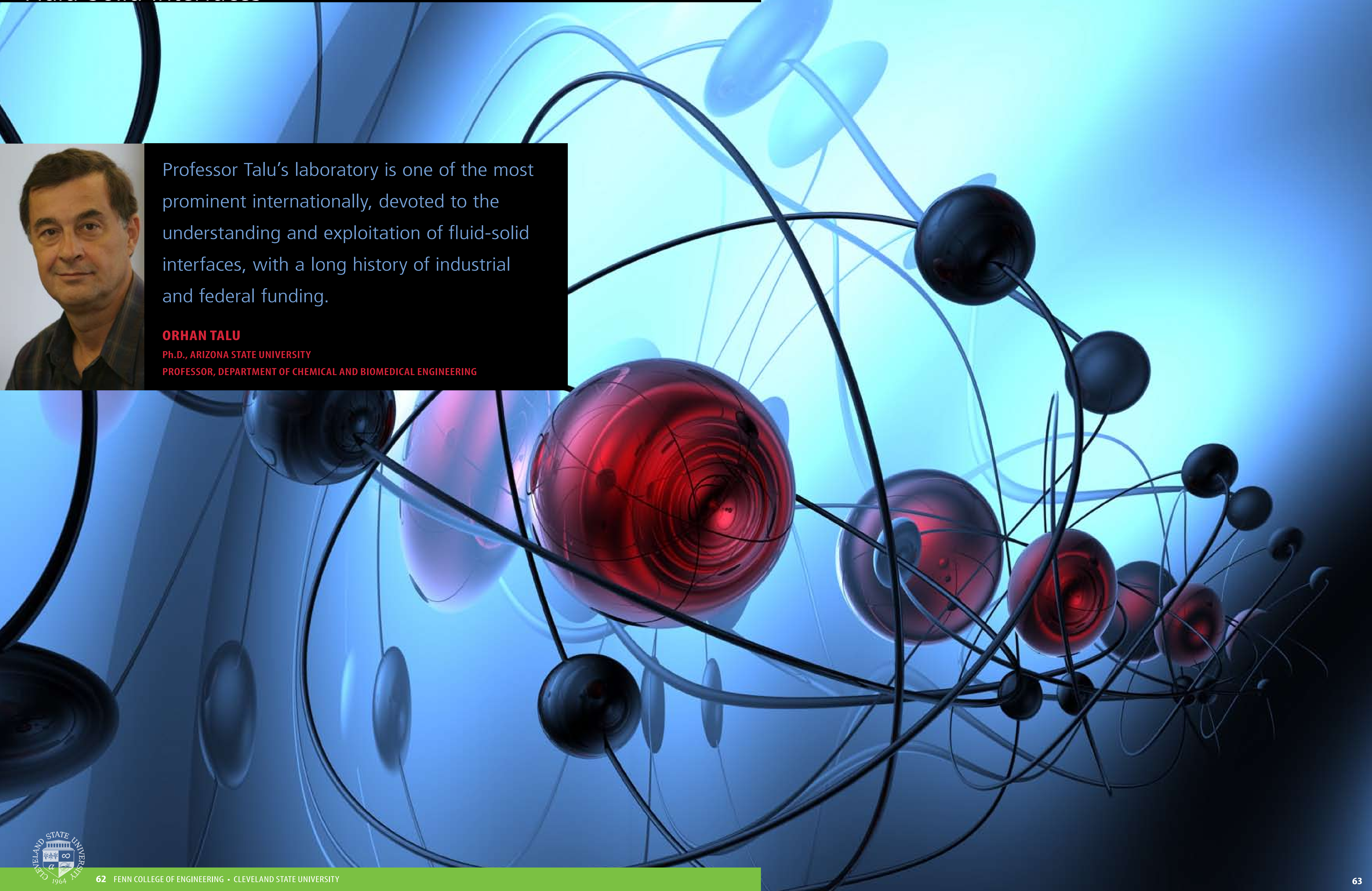
In line with Professor Sridhar's research goals, this project is investigating important problems and solutions for building a sensor system that is usable by transportation engineers to collect data about traffic in short-term work zones, and then use this data to characterize and measure driver behavior. The key contribution of this research is that it enables the use of this system by transportation engineers without any need for special programming on their part.

LOW-POWER SENSOR NODE ARCHITECTURE FOR HIGH-FREQUENCY DATA ACQUISITION AND ANALYSIS

The need for high-frequency signal acquisition and processing is becoming increasingly prevalent in sensor networks. Applications that require high-frequency data sampling are presently at a disadvantage; applications that only sample at high data rates (and not process any of it locally) end up transmitting large quantities of data, greatly reducing network lifetime. Other applications that do use in-network signal processing rely on power-hungry motes.

This project presents LAKON, a mote architecture capable of on-board signal processing of high-frequency data that provides a middle ground for more general classes of applications that require signal processing. Professor Sridhar's design takes advantage of an energy-efficient on-board digital signal processor (DSP) that can be intelligently enabled on demand.

Fluid-Solid Interfaces



Professor Talu's laboratory is one of the most prominent internationally, devoted to the understanding and exploitation of fluid-solid interfaces, with a long history of industrial and federal funding.

ORHAN TALU
Ph.D., ARIZONA STATE UNIVERSITY
PROFESSOR, DEPARTMENT OF CHEMICAL AND BIOMEDICAL ENGINEERING

Figure 1

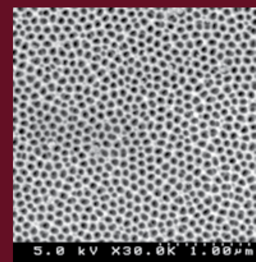


Figure 2

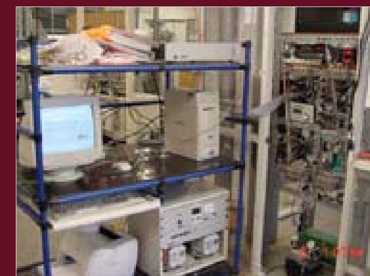


Figure 3

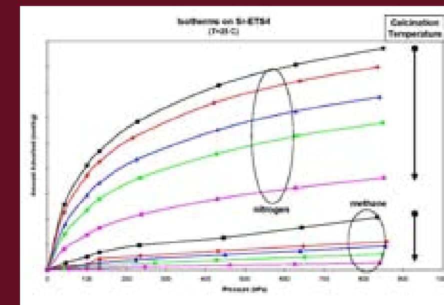


Figure 4

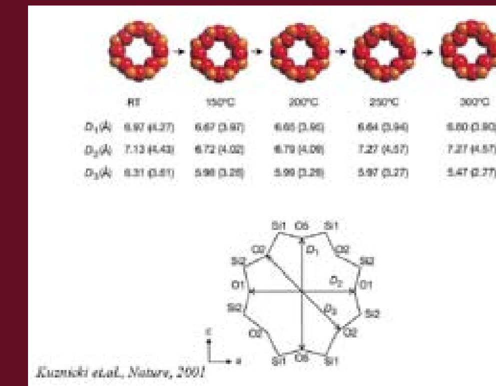


Figure 5

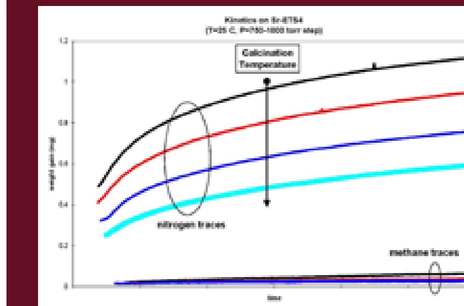


Figure 6


Figure 7

When we look at the top of a table, the interface between the table and the air above it seems very clear to the naked eye. At the molecular scale though, the interface between a solid and a fluid is not so clear and it is full of amazing features; the density of the fluid phase (air) rapidly increases as the solid is approached, then drops to zero at a sub-molecular distance. Sometimes, a layering phenomenon is observed, other times one or more components of a fluid mixture are enriched at the interface. The behavior is different for different fluids, such as gases, vapors and liquids, and for different solids such as oxides, carbonaceous materials, and metals. The interfacial properties depend on the type, temperature, pressure and composition of the fluid as well as on the physical nature of the solid. Nature an d mankind exploit the rich physical-chemical nature of fluid-solid interfaces. One of the most prominent research labs in the world devoted to understanding and exploitation of fluid-solid interfaces is at the Fenn College of Engineering under the direction of Professor Orhan Talu.

Professor Talu's research spans many length scales which simultaneously dictate interfacial phenomena. At or below nanometer length, molecular simulations are performed to explain the behavior of fluid molecules confined by solid surfaces. Solid material synthesis, characterization and optimization are often performed at medium length scales in the order of micro- to millimeter. Finally, process/product development is performed at realistic dimensions with meter scale equipment and process simulations. Figure 1 shows some pictorial examples of these different length scales involved in the research being performed at the Fenn College of Engineering.

The concepts involved in interfacial phenomena are as wide as the length scales. Fundamental intermolecular forces responsible for the formation of any condensed state, such as a liquid, are also responsible for the formation of the interface. But unlike bulk fluids, the interface is discontinuous and anisotropic at the molecular scale due to the existence of the solid. Thorough understanding and manipulation of intermolecular forces in confined spaces is essential to exploit the interfacial phenomena.

Manipulation of intermolecular forces on a given subject fluid is possible by tailoring the solid; this is a unique feature and main advantage of fluid-solid interfaces. Often, the solid is microporous with Angstrom size pores (1 Å = 0.1 nanometer) to maximize the interfacial surface area per volume. Thus, tailoring the solid involves manipulation of physical properties of the solid such as its pore size as well as altering the chemical nature by surface modifications. Figure 2 shows an electron micrograph (SEM) picture of a highly ordered porous alumina material produced in Professor Talu's labs as an example. Research on fluid-solid interfaces is intricately linked with material science.

Intermolecular forces are not, in general, directly measurable. They determine the behavior of individual molecules (particles) in a field imposed by other molecules of the fluid and the solid. One can only observe how a very large number (in the order of 10^{23}) of molecules behave in experiments on equilibrium and kinetics. Great strides have been made in recent decades in translating the intermolecular forces to equilibrium and kinetic properties via molecular simulations. Yet, even the state-of-the-art in these demanding computations are still not accurate enough to circumvent the experimental measurements completely. Simulations and experiments are often performed by different research groups guided by each other. In addition to performing simulations, Professor Talu's facilities house equipment to measure both equilibrium and kinetic interfacial properties (Figure 3 shows an example) extending to fluid mixtures which can only be performed in a very few labs in the world.

Measurements of mixture properties in a system which is already heterogeneous (with fluid and solid phases present) is at least an order of magnitude more complicated than measurements of pure fluid properties. Professor Talu's research group works on classic theoretical models of equilibrium and kinetics in interfacial phenomena to predict mixture properties from pure components in order to avoid these complicated experiments in the future. Although the state-of-the-art in mixture predictions has advanced substantially by theories/models proposed by Professor Talu and others, the predictions are still not accurate enough rendering simultaneous theoretical and experimental effort necessary for the time being.

All areas/activities listed above are scientific investigations at lab scale. Engineers put their knowledge in use to better the mankind. The last part of Professor Talu's effort is devoted to process development integrating equilibrium and kinetics with large scale system dynamics. Process simulations are often utilized to discover the range of possibilities on a computer. The simulation effort in Professor Talu's labs is used to narrow the field for design considerations. The final design of a process or product almost always involves pilot, proto-type testing at realistic scales and conditions.

Given the complexity of fluid-solid interfaces, it is not surprising to see a high level of collaboration between academia and industry in the field. Often the collaboration involves competitive development effort involving classical modeling, simulations and experiments. Professor Talu has had a long history of industrial collaborations for over 20 years involving all aspects of fluid-solid interfaces.

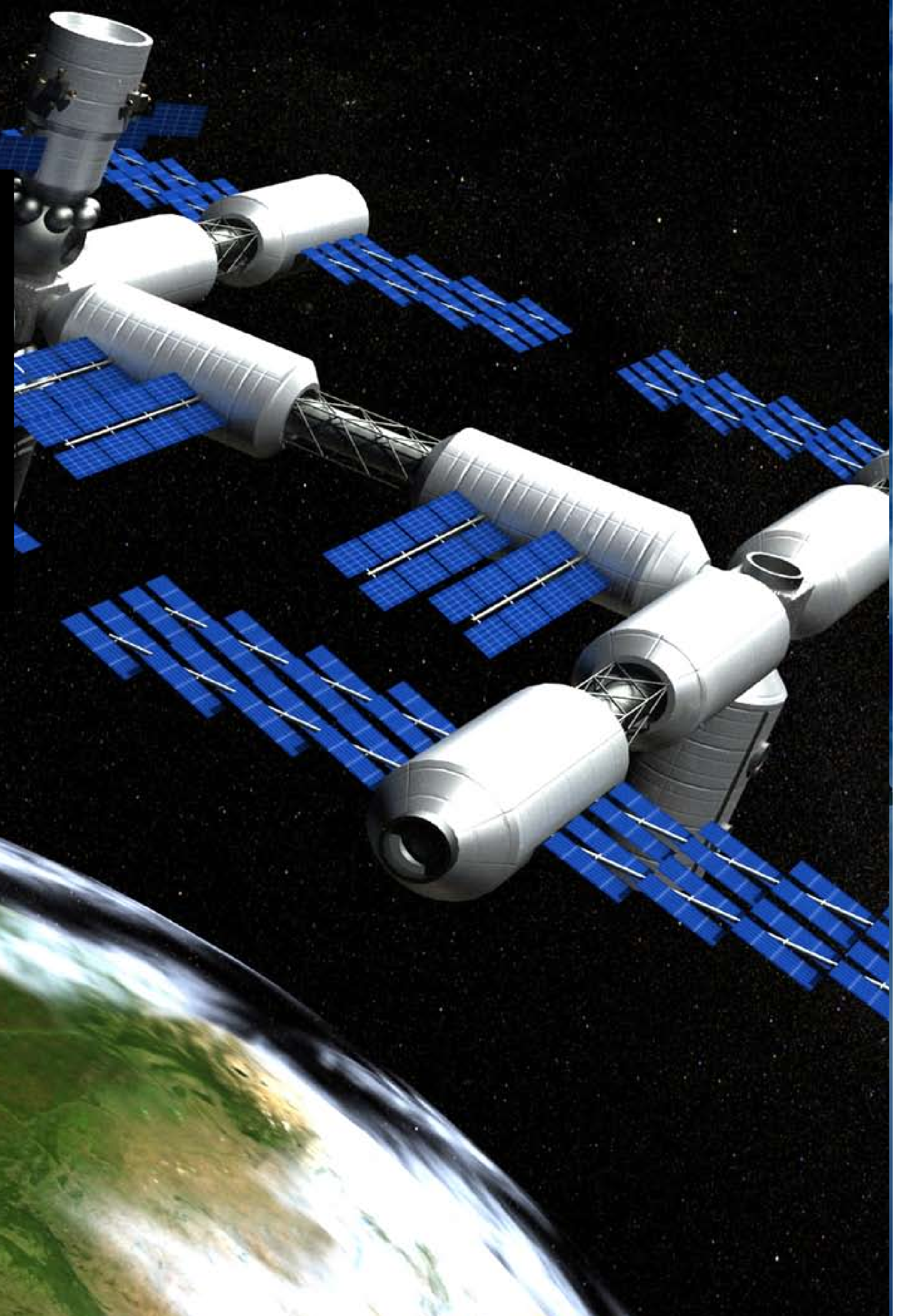
One example of his collaborative work is the development of Molecular Gates™ technology to upgrade off-grade natural gas from various sources. This effort was partially supported by NIST/ATP program with Engelhard Corporation (now BASF Catalysis LLC) as the industrial partner, and with Cleveland State University and the University of Massachusetts as academic partners. Off-grade natural gas contains large amounts of nitrogen (up to 30%) which lowers the calorific value. Long standing technologies has been designed for large volume processes where economies of scale can be realized. Often the off-grade natural gas with medium to small flows is burned, flared at location.

Designing a medium to small size process to remove nitrogen from methane (main constituent of natural gas) is not a trivial task. Traditional approaches such as membrane separations or gas absorption are not feasible because of many factors such as low selectivity, reliability, solvent contamination, etc. Many adsorbent solids had been evaluated for the process in the past, yet none was identified with enough nitrogen selectivity and capacity to make the process feasible. In fact, most solids are mildly selective to methane resulting in high pressure nitrogen product rather than methane. A few nitrogen selective solids differentiate between nitrogen and methane based on electronic structure (i.e. utilizing quadrupole moment of nitrogen), but these do not have high enough selectivity and capacity for a feasible process. This all changed when the adjustable pore-size molecular sieve zeolite named ETS4 was discovered. Figure 4 shows the isotherms of nitrogen and methane on ETS4 measured in Professor Talu's labs. It is very clear that nitrogen is highly preferred by the solid (i.e. large nitrogen selectivity and capacity); this is not possible with other solids. Major effort was undertaken by the research collaboration to identify the structure and to elucidate the mechanism responsible for this observation. Figure 5 shows the subtle change in the pore opening of ETS4 by calcination temperature. This very fine pore-size control enables the solid distinguish between molecules with very small differences in size such as methane and nitrogen.

Size selectivity at molecular dimensions is often accompanied with very slow kinetics which can render a process fruitless. The next task was to determine the intrinsic kinetics of this system in order to evaluate if a feasible process can be designed. Figure 6 shows some of the results from Professor Talu's labs. By tailoring the solid product through surface chemistry (cation type) and by treatment temperature, it was possible to find an optimum combination of equilibrium and kinetics to remove nitrogen from methane at ambient temperature. Armed with favorable equilibrium and kinetics data, the process was ready for development.

The final task was to evaluate an actual Pressure Swing Adsorption (PSA) process by simulations and pilot scale testing (example in Figure 4) to optimize conditions. Indeed, the process conditions are optimized for each feed gas in PSA operations. Nitrogen rejection with Molecular Gates was optimized for a test site at Hamilton Creek, Colorado as a demonstration project at the end of NIST/ATP program. The unit operated with 99% reliability over two years during the demonstration period. The project was highlighted as a "Gem" project by NIST (see http://www.atp.nist.gov/gems/99-01-6041gem.pdf). Figure 7 shows a picture of the unit used at Hamilton Creek. Now the technology is in commercial use. It has also been extended to simultaneously remove carbon dioxide with new applications in coal bed gas, biogas and landfill gas.

Molecular Gates is just one example of the work performed in Professor Talu's labs at the Fenn College of Engineering. It exemplifies the many different length scales, different physical phenomena, and engineering involved in fluid-solid interfaces. It is also an exemplary project for academy-industry-government collaboration. The ongoing research effort on fluid-solid interfaces at the Fenn College varies from fundamental studies to applied research like the one described here. As such, Professor Talu's labs have been supported by agencies (e.g. NSF, NIST, NASA, DOE, etc.) and by industrial concerns (e.g. Michigan Consolidated Gas, GE/Lighting, Air Products and Chemicals, British Oxygen Corp., Engelhard Corp., Eaton Corp., etc.)



Professor Tewari's latest research activities include the development of better coating for silicon-base ceramics, the study of directional solidification of metallic alloys in low gravity on the International Space Station, and the improvement of bone tissue implants.

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Ph.D., PURDUE UNIVERSITY
PROFESSOR, DEPARTMENT OF CHEMICAL AND BIOMEDICAL ENGINEERING

Professor Surendra Tewari has decades of research experience in the improvement of the behavior of materials used in aerospace — and not only — applications. His latest endeavors include the development of better coating of silicon-base ceramics, the study of directional solidification of metallic alloys on the International Space Station, and the improvement of bone tissue implants.

ENVIRONMENTAL BARRIER COATING FOR SILICON-BASED CERAMICS

Silicon-based ceramics, such as SiC/SiC composites, are leading candidate materials for the hot-section components of next generation gas turbine engines, because of their low density, outstanding high-temperature strength, and thermal shock resistance. In oxidizing environments, these materials develop a silica scale which protects them from further oxidation. However, in moisture-containing environments, silica reacts with water and rapidly evaporates leaving the surface unprotected. Since water is a by-product of fuel combustion, these ceramics cannot be used in gas turbine engines unless an effective environmental barrier coating is available to prevent moisture from transporting to the substrate.

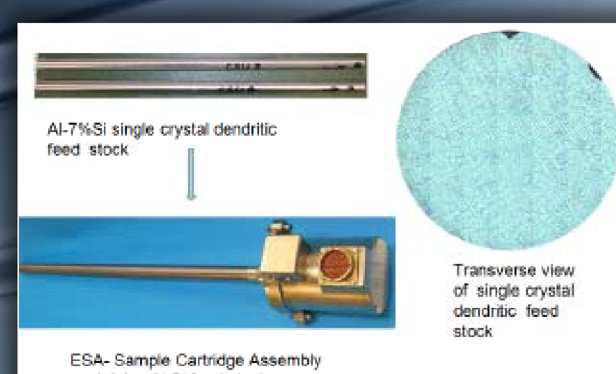
Current state-of-the-art plasma-sprayed environmental barrier coatings developed for SiC/SiC composites provide adequate protection only up to about 1275°C. Professor Tewari's research aims to develop environmental barrier coating processes and to improve the fracture toughness of the coating. Slurry-based coating processes are being developed to create a bond coat that provides crack-deflection as well as process flexibility. The outer coatings, based on rare earth silicates, will provide a water vapor-resistant, high insulating surface layer.

Uncoated SiC (Figure a) undergoes surface damage due to moisture in a simulated combustion environment (100 thermal cycles from 1350°C to room temperature). The coated sample does not show damage at the coating-substrate interface in SiC/SiC composite (Figure b).

DENDRITIC DIRECTIONAL SOLIDIFICATION OF METALLIC ALLOYS ON THE INTERNATIONAL SPACE STATION

It is of great significance to understand and control how single-crystal alloy castings solidify. Single-crystal castings are critical components in high-temperature gas-turbine engines that are used in high-speed aircraft, and land-based power turbines. Models of dendritic solidification that are used to predict the microstructure of alloy castings rely on the assumption of diffusional transports of both heat and solute. The thermosolutal convection of the liquid in, from, or close to the solid- liquid region of solidifying alloys masks the diffusional processes and is responsible for macrosegregation. Nevertheless, it is expected that this thermosolutal convection will be significantly reduced in microgravity and the convection will be confined mainly to the minor flows of interdendritic liquid required to satisfy solidification shrinkage. Morphological features, metrics, and segregation in samples directionally solidified in an earth-based furnace and in samples grown in microgravity will be quite different.

As part of a NASA-European Space Agency (ESA) collaborative research project, the Space Shuttle Discovery (STS 128), launched on August 28, 2009, carried two sample cartridges containing Al-7 wt pct Si cylinders grown at Cleveland State University to the International Space Station (ISS). One of these samples was re-melted and directionally solidified by astronauts in space in the ESA-Materials Science Laboratory Low Gradient Furnace on February 2, 2010. The furnace is powered by the NASA-Materials Science Research Rack I, which was also launched on STS 128. Space shuttle Endeavour brought back this low gravity processed cartridge on February 21, 2010. This sample is now back at CSU, from where it originated, and is being characterized by Professor Tewari and his team. The second sample is planned to be processed during later part of 2010. These are the only two US materials processing experiments being carried out on the Space Station.

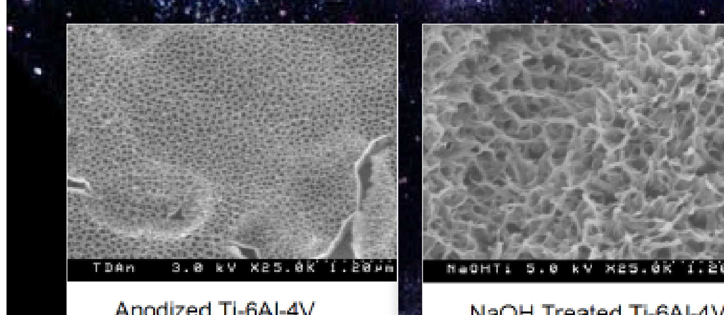


ATTACHMENT AND PROLIFERATION OF OSTEOBLASTS ON NANO-TEXTURED TI-6AL-4V SURFACES

Because of its low cytotoxic leachability, low density and adequate mechanical properties, the Ti-6Al-4V alloy is extensively used for bone tissue implants, such as dental implants, hip replacements, and other types of orthopaedic surgery. Attachment, migration, and proliferation of bone-forming osteoblast cells on the implant surface immediately after the surgery determine how readily the implant becomes integrated into the surrounding bone by the formation and attachment of new bones on its surface. It is believed that the quality of this initial osteo-integration also determines the useful life of these implants. An inadequate initial integration leads to an accelerated implant loosening, which is a serious issue in orthopedic surgery, since the replacement of an artificial hip tends to be less successful than the initial hip replacement surgery.

Osteoblasts, the bone forming cells, are typically about 10 µm in diameter. Their cytoskeleton is made up of a complex network of about 10-20 nm diameter microfilaments. Their biological interaction with an implant substrate is therefore a strong function of its micro and nano-surface topography and its surface chemistry. Influence of surface nanotopography on attachment, migration, and propagation of osteoblast cells is being investigated under this project.

Anodization creates a thin titanium oxide surface, containing about 50 nm diameter pits, on otherwise a smooth surface. The NaOH etched surface also contains nanometer size pits, but its spongy topography, containing spiky features, more closely resembles cellular cytoskeleton. Preliminary experiments indicate that NaOH etched topography is more conducive for cell adhesion. Via this research, Dr. Tewari, teamed with Dr. Joanne Belovich from the Department of Chemical and Biomedical Engineering of Cleveland State University and Dr. Ron Midura from the Lerner Research Institute of the Cleveland Clinic, is aiming to improve the life of titanium alloy implants.



Anodized Ti-6Al-4V
NaOH Treated Ti-6Al-4V

Biosensors and Renewable Energy Devices

Professor Yau's research activities are focused on two themes — developing techniques for detection of substances for biomedical applications and making devices for converting and storing renewable energy.

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ASSOCIATE PROFESSOR, DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

The 21st century is the age, in which scientific and technological wonders such as information technology, personal electronics, advances in biomedicine and products of nanotechnology bring about new outlooks. Mankind in this century is expected to have a longer life with improved quality. However, it is also a time for mankind to confront critical global issues such as energy shortage, global warming and environmental pollution.

Presently, the world is facing an unprecedented energy crisis, which is triggered by the increasing global energy consumption and the increasing prices of fuels in recent years. The majority of the fuels being used today, such as petroleum and coal, are fossil in nature. The production of some of these fuels has peaked or is about to peak. The high energy consumption has caused pressing environmental issues that we are presently experiencing. The most severe ones are environmental pollution and global warming which resulted in a changing climate. To relieve the adversities described above, mankind is turning to renewable energy resources for solutions.

Professor Yau's research activities are focused on two themes, namely, developing techniques for detection of substances for biomedical applications and making devices for converting and storing renewable energy. The current research projects that are carried out in his laboratory are described as follows.

ULTRASENSITIVE BIOSENSING: THE ENZYMATIC FIELD-EFFECT TRANSISTOR

The present thrust for ultrasensitive detection of substances in areas such as early detection of diseases, environment protection and homeland security, demands techniques that provide unprecedented detection sensitivity. Recently, Professor Yau invented a bioelectrochemical detection technique, which allows him to push the detection limit of biosensors from the milli-molar (10^{-3} M) to the pico-molar (10^{-12} M) resolution range. By applying a gating voltage to the enzyme-immobilized working electrode of a conventional electrochemical cell, the biocatalytic output current of the detector was increased significantly, resulting in voltage-controlled amplification of the output current. The current amplification could be reversibly controlled by the applied voltage. Professor Yau applied this technique to the bio-catalyzed oxidation of glucose and ethanol using immobilized glucose oxidase and alcohol dehydrogenase, respectively. The enzymes' bio-specificities were preserved in the presence of the voltage. The voltage-controlled amplification of the output current was also observed in the reduction of hydrogen peroxide using immobilized microperixidase, a biomolecule that reduces H_2O_2 to water.

The detector, with its output current controlled by a voltage applied at a third electrode, behaves as a field-effect transistor, whose current generating mechanism is the conversion of a substance (the analyte) to a product using an enzyme as catalyst. The realization of the enzymatic transistor (Figure 1) has significant technological implication. Professor Yau's demonstration of the operation of the transistor shows that the kinetics of the biocatalyzed reactions can be controlled by a voltage. Controlled reaction kinetics of biological catalysis has been achieved using an electrostatic technique. The technique allows independent controls of the thermodynamics of an electrochemical system and the quantum mechanical tunneling at the interface between electroactive molecules and the working electrode by applying a voltage to the electrode.

NANOPARTICLE-BASED SENSORS

The newly-discovered colloidal silicon nanoparticle is used as the sensing element for non-enzyme sensors for substances that are important in food industry, biomedicine and environmental applications. With this kind of sensor, Professor Yau has demonstrated direct electrochemical amperometric detection of different forms of sugar (glucose, fructose and lactose), dopamine, hydrogen peroxide and phenol. In the sensing of glucose, the sensor showed exclusive detection of glucose in the presence of interfering species within the physiological concentration ranges of these substances. The sensor also showed negligible electrode poisoning and detection stability over a 14-week period of repeated use. A comparison between the glucose detection characteristics of the nanoparticle-based sensor and an enzyme-based shows an enhanced amperometric response of the particle sensor. Professor Yau's results reveal several advantages of using the silicon nanoparticle in bioelectronics. The nanoparticle appears as a suitable active material for the making of implantable devices and nanoscale devices.

SILICON NANOPARTICLES AS ELECTROCATALYST FOR RENEWABLE FUELS

Fuel cells utilize nature's renewable-energy resources such as hydrogen and bio-derived alcohol to generate electricity, and, since fuel cells produce insignificant amount of carbon dioxide compared to the combustion engine, fuel cell technology is environment-friendly. While large-scale high-power fuel cells operating on hydrogen have already been deployed in automobiles, scaled-down low-power micro-fuel cells that operate on alcohols (methanol or ethanol) have recently gained significant attention due to the rapid growth of portable and wireless consumer electronics over the past few years. To develop a viable fuel cell technology, new electrocatalysts, especially those with novel properties due to their having dimensions on the nanoscale, must be discovered to meet the requirements impose by fuel cell applications. Conventionally, nanoparticles of platinum (Pt) and Pt-based bimetallic alloy systems are used as catalysts for fuel cell operation. Although fuel cells that use precious metals as catalysts are commercially available, the high cost of precious metals (about $8,000 per pound for Pt) makes them economically non-viable. Thus, one of the major challenges for fuel cell technology is to use catalysts that are non-precious metals. Professor Yau's research group has shown that ultra-small (1 nm and 2.8 nm) light emitting colloidal silicon nanoparticles (Figure 2a) behave as electrocatalysts for the oxidation of ethanol and methanol. Particle immobilized silicon and carbon paper electrodes show an onset of catalysis occurring at potentials between -0.3 V and 0.05 V vs. Ag/AgCl (between 0.31 V and 0.66 V vs. RHE) at neutral pH. Both the onset potential and the strength of catalysis are dependent on particle size. Cyclic voltametric and chronoamperometric measurements were used to differentiate the oxidation current from charging current. A prototype double-compartment fuel cell has been constructed and tested, using the particles as the anode catalyst, in order to demonstrate the potential of the particles in fuel cell applications. The particle-catalyzed oxidation of the fuels has been studied under acidic and alkaline conditions. It was found that the catalytic activity undergoes at least a 50-fold increase under alkaline condition compared to under acidic condition. An unexpected light dependence of the catalytic current was observed. A significant increase in the catalytic current is obtained when the catalysis is performed in darkness (Figure 2b).

SUPERCAPACITORS

Supercapacitors are electrochemical devices. They can be used to store electrical energy generated by intermittent renewable energy sources such as wind or solar radiation to ensure that energy is available at all times. Supercapacitors are well suited to act as rechargeable stand-alone power sources for portable electronic equipment with moderate energy demands. Most devices presently using battery power supplies have long recharge times and need to be charged overnight. This has come to be accepted as a limitation of the current technology, but supercapacitors offer the opportunity to create devices that can be recharged quickly, perhaps in just a few seconds. Development in supercapacitors requires novel nanoscale/nanoporous material systems for higher energy storage capacity and durability.

Professor Yau's group has developed a composite material consisting of polyaniline (PANI), a conducting polymer, and ultrasmall silicon nanoparticles for making supercapacitors (Figure 3). Because of the hybrid nature of its capacitance, the composite shows a significantly enhanced specific capacitance of 409.27F/g. The enhanced capacitance results in high power (220 kW /kg) and energy-storage (30 Wh/kg) capabilities of the composite material. The specific capacitance of the composite electrode was observed to be stable during 2000 charging-discharging cycles.

FLEXIBLE SUPERCAPACITOR SHEETS FABRICATED USING A "BRUSHING-ON" APPROACH

Flexible electronics and display, in which active devices such as transistors and LEDs are fabricated on flexible electrode materials, are of current interests from the consumer electronic and military sectors. To utilize the flexible devices, flexible energy conversion and storage devices with high energy storage and power density capabilities needs to be realized and integrated with the active devices. Electrochemical supercapacitors with high energy storage and power density capabilities, small sizes, and light weights are potentially capable of powering flexible devices. Professor Yau has produced flexible sheets of supercapacitors using a simple "brushingon" technique with conducting polymers and carbon nanotubes. Figure 4a shows the capacitor sheet and Figure 4b shows that three LEDs were lit up by the capacitor sheets. The capacitor sheets also showed good stability during 600 charging/discharging cycles. His preliminary results indicate an inexpensive technical approach for high-throughput fabrication of flexible supercapacitors.

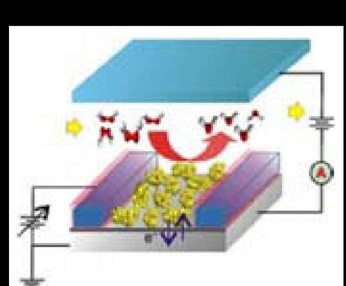

Figure 1

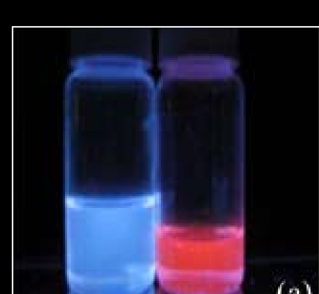

Figure 2a

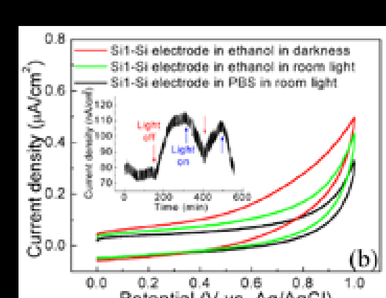

Figure 2b

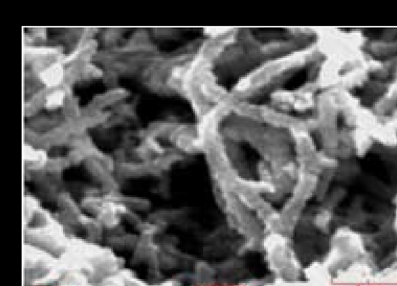

Figure 3

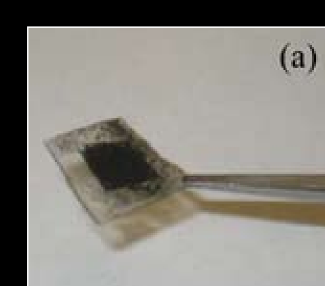

Figure 4a

Figure 4b

The Institute was formed in March 2009 to develop a closer partnership between the Fenn College of Engineering and industry. FRDI is structured to be a one-stop engineering R&D support entity involving expert faculty, engaged students, dedicated staff and physical facilities. Universities, particularly urban, can play a significant role in regional economic development. A structured and focused relationship can eliminate the inefficiencies that frequently surface in interactions between universities and industry. Once properly planned and implemented, such partnerships can go a long way to bridge the cultural differences between academia and industry.

FRDI HAS FOUR MAJOR UNITS:

- Industry Joint Research Projects
- Service Learning
- Industry Services and Contracts
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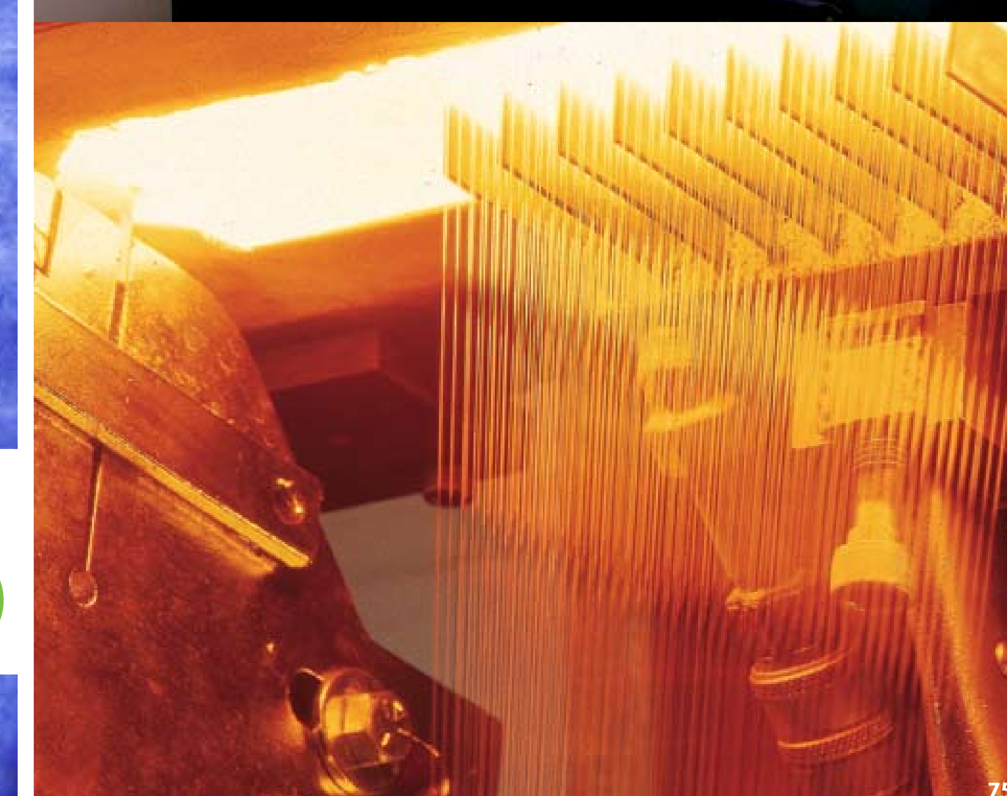

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