



2016

# Industry-Nominated Technology Breakthroughs of NSF Industry/University Cooperative Research Centers



# Industry-Nominated Technology Breakthroughs of NSF Industry/University Cooperative Research Centers 2016

Work culminating in 2014 and 2015



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*Front cover credits:*

Living Earth HD real-time weather.

CHREC Space Processor

A wind turbine. Credit: Wind Energy Development Programmatic Environmental Impact Statement.

CAKE Wireless Deep-Brain Stimulation With Magnetoelectric Nanoparticles.

Protecting Against State-of-the-Art Cyber Attacks through Opaque Control-Flow Integrity at NCSS

Distributed run-time management for multi-agent system at CES

3D Printing of Smart Structures with Embedded Optical Fiber Sensors, Courtesy of Moog Inc.

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# The NSF Statutory Mission

AN ACT To promote the progress of science; to advance the national health, prosperity, and welfare;  
and to secure the national defense; and for other purposes.

*—From the National Science Foundation Act of 1950 (P.L. 81-507)*



# The NSF Vision

NSF envisions a nation that capitalizes on new concepts in science and engineering and provides global leadership in advancing research and education.

*—From "Empowering the National Through Discovery and Innovation, NSF Strategic Plan for Fiscal Years 2011-2016"*





# Preface

Over-time, many I/UCRCs have become recognized for innovative, cutting edge research. They have developed impressive track records for exploring innovative approaches to some of the nation's most pressing research problems through leveraged collaborations and team science.

Industrially relevant scientific breakthroughs and advances do not typically happen in silos. Many result from multi-disciplinary collaborations that involve creative scientists from both academe and industry. The National Science Foundation's Industry/University Cooperative Research Center (I/UCRC) Program is designed to set up the conditions that nurture such collaborations.

The NSF's I/UCRC Program is located organizationally within the Directorate for Engineering's Division of Industrial Innovation and Partnerships (IIP). A primary strategic goal of the IIP Division is to foster the development of sustained university/industry research partnerships. These are focused on pre-competitive research within each center's research domain, on trusted networks, and on dynamic technical interrelationships.

For over four decades the I/UCRC Program has catalyzed partnerships among industry sectors, academe and government. As of December of 2015, there were over 77 active centers involving approximately 180 universities and 775 industry partners.

Each Industry & University Cooperative Research Center (I/UCRC) conducts pre-competitive research that is of interest to its industry sponsors and to the universities with which they are involved.

A unique feature of I/UCRCs is that they do not conduct industry's research. On the contrary, industry joins and supports centers that have research areas and missions in which they are interested. Faculty present proposals annually. Before advising centers regarding which research they would like to see conducted, industry representatives offer their industrial perspectives on the proposed work and suggest modifications. This sponsoring industry feedback significantly enhances the quality of the proposed work and makes it more relevant to industry's needs.

The NSF provides I/UCRCs with a modest amount of funding as base support. The I/UCRC partnership model, which is at the heart of the program, requires that the majority of center funds be contributed by corporate sponsors. In 2015, the NSF's Engineering and Computer Information and Science Engineering Directorates invested a combined total of approximately 20 million dollars in the I/UCRC program while industry invested in excess of \$130 million dollars - primarily in the form of center memberships. The vast majority of industry funds were used to provide direct research support.

Each center has its own, industry-led industrial advisory board. Each center's IAB oversees its research program and activities and advises university leadership and researchers on user-inspired fundamental research; projects that are jointly funded by pooled industry sponsor dollars. Each center develops a shared project research portfolio. Within the portfolio, research is then cooperatively defined and governed by terms of the NSF/IUCRC Membership Agreement that all centers use. Sponsors then have early access to and non-exclusive access to intellectual property that results from the research.

## THE 2016 COMPENDIUM

This 6th edition is intended to acquaint readers with how I/UCRC knowledge and technology are being discovered, developed and translated into industrially and/or commercially and industrial advances and applications. It catalogues technological breakthroughs and advances that industry representatives believe are attributable to specific Industry & University Cooperative Research Centers (I/UCRCs).

Beginning in 2007, the first of five previous editions of the *Compendium of Industry-Nominated Technology Breakthroughs of I/UCRCs* was published. Previous compendia were cumulative; that is, they contained both newly nominated breakthroughs and selected, still relevant updated entries from previous editions.

With this 6th edition, for the first time, the content has been limited to work that was conducted during the timeframe that began with the start of the 2013-14 academic year (September of 2013) and concluded at the end of the 2015 calendar year.

## THE NOMINATION GENERATION PROCESS

Each entry in this 6th edition was nominated by a member of the center's industrial Advisory Board (IAB). To start the process each I/UCRC center director was asked to provide the editor with contact information for industrial advisory board (IAB) member/scientists whom they viewed as particularly knowledgeable about their center's research program and its impacts on science and technology

Nominations were sought from industrial board representatives from each center for which contact information was provided. The IAB representatives whose names were provided by their center's director were approached by the editor to determine whether any of the center's research endeavors that had been ongoing since September 2013, met the following definition of a technological advance or breakthrough:

TECHNOLOGY BREAKTHROUGH DEFINITION: An I/UCRC-attributable technological advance or breakthrough is defined as center-related research that either directly or indirectly led to, or likely will lead to, significant process improvements, new processes or techniques, new/improved products or services, and/or economic benefits such as cost savings, increased profits and/or job growth for the sponsor, the industrial sector, and/or the nation's economy.

When an IAB representative viewed any specific center work as meeting the breakthrough definition, then they were encouraged to nominate the work for possible inclusion in the compendium. As soon as a piece of work was nominated, the editor began working with the involved university scientists and the center director to produce the individual entries contained herein.

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# List of Nominated Engineering-Funded Centers

There are both Engineering and CISE-funded centers. The following is a list of Engineering centers that have been nominated for inclusion.

Berkeley Sensor and Actuators Center (BSAC)

Center for Innovative Instrumentation Technology (CiiT)

Center for Advanced Design and Man of Integrated Microfluidics (CADMIM)

Center for Advanced Forestry Systems (CAFS)

Advanced Processing and Packaging Studies (CAPPS)

Center for Advanced Vehicle and Extreme Environment Electronics (CAVE<sup>3</sup>)

Center for Child Injury Prevention Studies (CChIPS)

Center for the Design of Analog-Digital Integrated Circuits (CDADIC)

Center for Dielectrics and Piezoelectrics (CDP)

Center for Electromagnetic Compatibility (CEMC)

Center for Tire Research (CenTiRe)

Center for Electrochemical Processes and Technology (CEProTECH)

Center for Health Organization Transformation (CHOT)

Laser and Plasma for Advanced Manufacturing (LPAM)

Center for Particulate and Surfactant Systems (CPaSS)

Center for Pharmaceutical Development (CPD)

Ceramics Composites and Optical Materials Center (CCOMC)

Cooling Technologies Research Center (CTRC)

Center for Energy-Smart Electronic Systems (ES2)

GRIID-Connected Advanced Power Electronic Systems (GRAPES)



Science Center for Marine Fisheries Science (SCeMFIS)

Smart Vehicle Concepts (SVC) Center

Wind-Energy Science, Technology and Research (WINDStar)

# List of Nominated CISE-Funded Centers

The National Science Foundation's Directorate for Computer and Information Science and Engineering (CISE) supports research that helps the nation uphold a position of world leadership in computing, communications, and information science and engineering. CISE also promotes understandings of the principles of advanced computing in service to society. The directorate provides support for number of I/UCRCs in computer and information science and engineering. By doing so it helps develop and maintain cutting-edge national computing and information infrastructure for research and education generally, and contributes to the education and training of the next generation of computer scientists and engineers.

Center for Advanced Knowledge Enablement (CAKE)

Center for e-Design

Center for Embedded Systems (CES)

Center for High-Performance & Reconfigurable Computing (CHREC)

Center for Hybrid Multicore Productivity Research (CHMPR)

Visual and Decision Informatics (CVDI)

Cyber-Physical Systems for the Hospital Operating Room (CyBHOR)

Intelligent Maintenance Systems (IMS)

Net-Centric & Cloud Software & Systems (NCSS)

Security & Software Engineering Research Center (S<sup>2</sup>ERC)



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# Berkeley Sensors and Actuators (BSAC)

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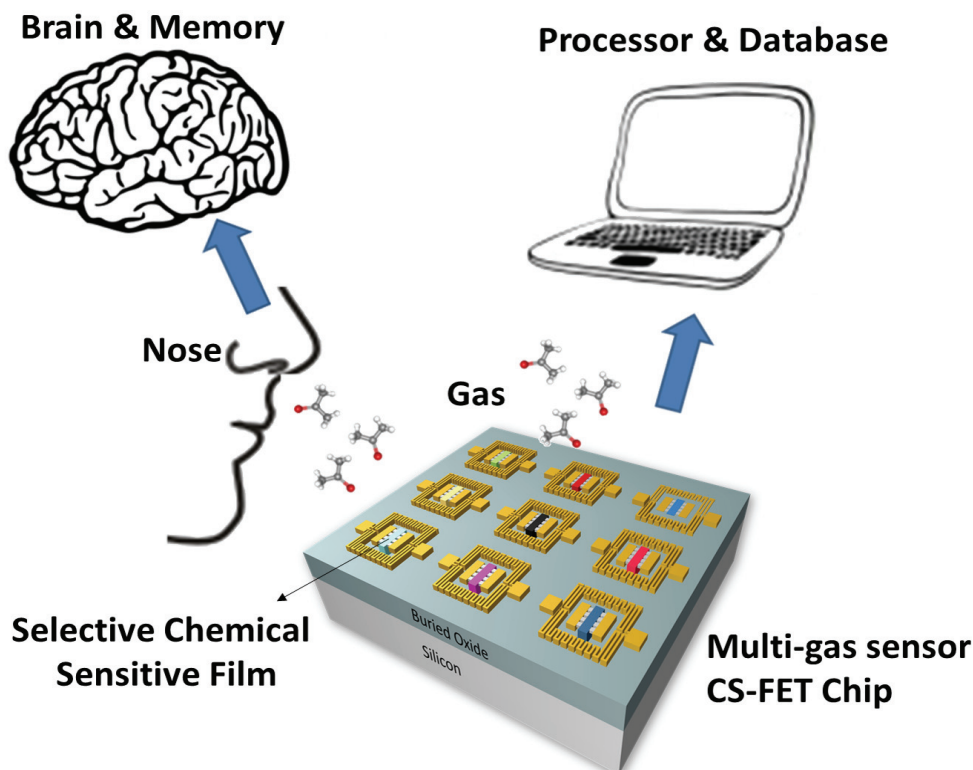
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## Chemical Sensitive Field Effect Transistor

Chemicals are all around us all. Sometimes they are toxic to our health. Knowing information about the chemical composition of our surrounding environment can allow us to take safety measures in attempts to protect our health; thus enabling preventive health-care to be practiced when needed more deliberately. Current research on wearable technology indicates that vital information about our physiological state can be ascertained by measuring and quantifying specific chemicals in our breath and sweat. Because of this, there are increasing demands for sensitive, selective and low power chemical sensors that can be integrated with personal mobile consumer electronics.



*The CS-FET is a low power gas sensor technology platform providing sensitive and selective multi-gas detection in a miniaturized, scalable single chip form-factor. Enabled by conventional silicon processing techniques, the CS-FET is a biomimicry of the human nose. Image provided by Ali Javey, EECS, UC Berkeley.*

## Berkeley Sensors and Actuators (BSAC)

The chemical sensitive field effect transistor (CS-FET) is a new chemical sensor technology platform developed at the University of California's Berkeley Sensor and Actuator Center (BSAC). Based on silicon, the CS-FET is structurally similar to the nanoscale electronic transistor switches (or FETs) that are used in our computers, except that electrical gates are replaced by a chemical sensitive film. Nanoscale means very, very small; usually considered to be between 1 and 100 billionths of a meter. Large arrays of CS-FETs can be functionalized with a variety of materials that interacts with specific chemicals, where such specific chemical interactions are transduced into electrical signals. By conditioning these signals, CS-FETs can provide a comparatively more accurate composition of mixed chemicals in an environment than existing technology where selectivity is a problem. This mechanism of selective chemical detection in the CS-FET platform is biomimicry of the human nose. Depending on the specific chemicals, CSFETs can be tuned to detect parts-per-million (ppm) or even parts-per-billion (ppb) levels of chemicals. These concentration ranges are the administrative levels of many toxic chemicals for human health and environmental safety.

All existing chemical sensing technologies have several disadvantages. These include: poor sensitivity; poor selectivity; bulky size/form-factor, and; high power consumption. Chemical sensors that have such disadvantages are hard to integrate with consumer electronics, thereby limiting their use to very specific industrial applications. The CS-FET breakthrough, because of its small and scalable size and low power consumption, can be integrated with wireless technology and/or energy harvesters such as solar cells or thermo-electrics, for remote applications such as real-time environmental chemical mapping over large areas.

Small form-factor, low power consumption, highly sensitive and selective CS-FET sensor platform opens up a variety of possibilities in the chemical sensing applications. Broad area deployment of wireless integrated CS-FET sensor nodes will enable 24/7 real-time monitoring of target chemicals within that area. This space monitoring would be achieved with lower power consumption and/or at new spaces compared to the present chemical sensors. CS-FETs in portable devices can chemically provide information regarding the environmental conditions around us and/or our day-day physiological state.

**Economic impact:** Because of the many advantages of the CS-FET sensor platform, such as small size, low concentration detection limit, good selectivity, and low power consumption, it will satisfy demands of many new applications; potentially replacing a considerable amount of present chemical sensing technologies. More significantly, wireless integrated CS-FET sensors should have huge economic impacts. A study shows that typically 50% of installation cost and 80% of installation time will be cut by changing wired connection to wireless connection of sensors used in industry. Global market size of hazardous fixed chemical detectors is roughly \$1B; roughly \$500M for portable detectors. In another report, the market size of wearable chemical sensors is expected to increase by about 30% every year in the next decade until 2025. Total market size of wearable sensors in 2025 will reach \$3B. Chemical sensors will occupy roughly 30% of this.

Due to similarity of the CS-FET to conventional field effect transistor (FETs) in computers, it will be possible to fabricate CS-FETs using existing and mature silicon processing techniques. This will definitely lower manufacturing costs. Current know-how in the semiconductor industry now can be transferred directly to CS-FET technology, which will drastically reduce R&D time/cost in Murata Manufacturing.

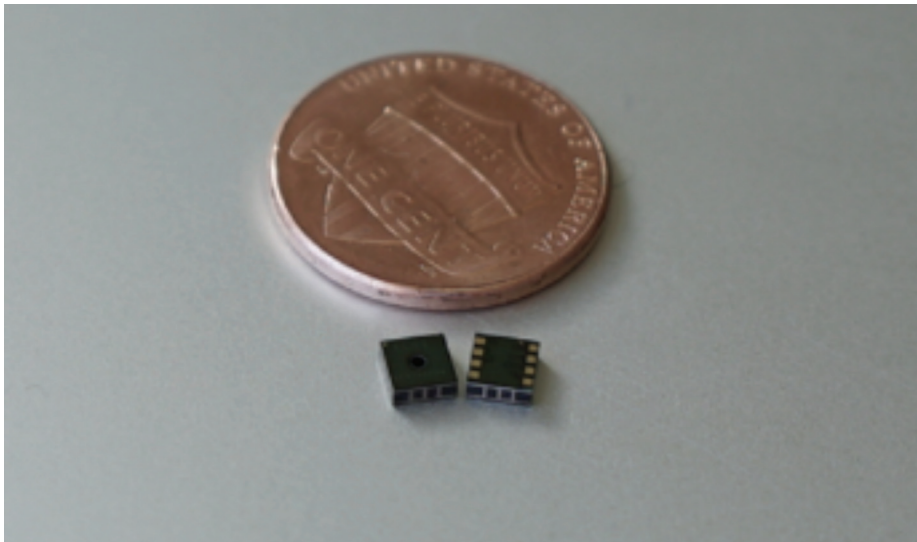
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## Ultrasonic Sensors for Consumer Electronics: MEMS Extension

Research at the Berkeley Sensor and Actuator Center (BSAC) has developed technology to make tiny, ultralow power ultrasonic sensors. These sensors use ultrasonic waves to detect objects and have applications in rangefinding, proximity, and presence detection. Multiple sensors can be used together to locate an object in three-dimensional space, enabling new user-interfaces such as gesture-based input. Because these sensors are ultra-low power, they can operate in small, battery-powered devices for months or years. The BSAC-developed ultrasonic sensor technology was licensed to Chirp Microsystems, a venture-funded start-up company that is working to commercialize it.

Ultrasonic sensors are widely used in everyday applications such as the parking-assist sensors in automobile bumpers. Relative to optical sensors, ultrasound has a number of advantages since it operates in all lighting conditions (total darkness to full sunlight), is insensitive to the color of an object, and it offers very precise range measurement. However, existing ultrasonic sensors are too big, too expensive, and too high power for use in most consumer electronic devices. The ultrasonic sensors developed by BSAC researchers operate at microwatt power levels, orders of magnitude lower than existing ultrasonic or optical sensors. BSAC's MEMS-based ultrasonic sensors are millimeters on a side, allowing them to fit into the smallest consumer electronic devices.



*Two ultrasonic sensors compared to a penny. Image provided by BSAC.*

MEMS based ultrasonic sensors have potential uses in consumer electronics devices such as laptops, tablets, and smart-phones. They may also be used in smart-home applications such as occupancy sensing. Because of their multiple potential applications in areas of extremely high consumer and industrial demand, their economic impacts should be substantial.

**Economic impact:** This technology is generating continuing interest and support from BSAC's industry members. This has led to another BSAC inspired startup, Chirp Microsystems (CM). CM



## **Berkeley Sensors and Actuators (BSAC)**

has commercialized it and is currently sampling products based on this NSF I/UCRC supported breakthrough technology. Commercial impacts are expected to exceed \$100M as measured by anticipated future valuations of Chirp. Chirp has been recognized by EE Times as "One of the 15 Startups to watch in 2015." A refereed paper from the Horsley/Boser research groups "3D Ultrasonic Gesture Recognition" received EE Times' designation as one of "5 Hot Papers" at the 2014 International Solid State Circuits Conference (ISSCC), the leading technical conference of the semiconductor industry. Because of their multiple potential applications in areas of extremely high consumer and strong industrial demand, their economic impacts should be substantial.

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# Center for Advanced Design and Manufacturing of Integrated Microfluidics (CADMIM)

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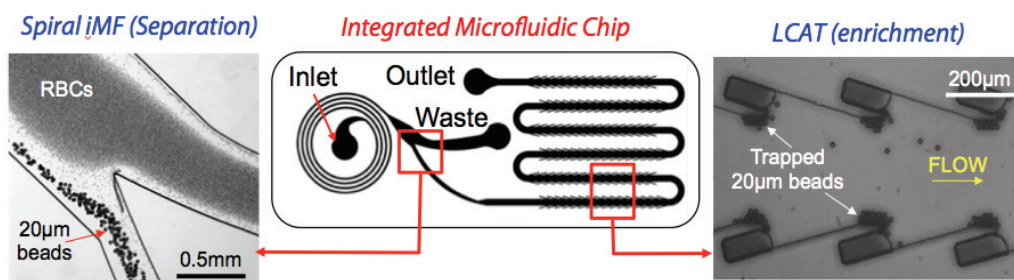
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## Integrated Microfluidic Device for Isolation & Enrichment of Rare Cells

High fidelity sorting, isolation, and concentration of target cells is a critical step in many diagnostic and therapeutic applications. Selective isolation of rare cells from complex mixtures, however, remains a critical challenge that has not previously been fully addressed. For example, cancer tumor cells that travel through the bloodstream can evolve to become clinically relevant as they are often the first indicators of tumor spreading. The moving tumor cells have the potential to inform physicians and guide therapy in lieu of more invasive tissue biopsies.

A CADMIM research team has successfully combined two microfluidic components for the selective isolation and enrichment of rare cells from untreated liquid samples - an inertial microfluidic (iMF) component and a lateral cavity acoustic transducer (LCAT) component. Microfluidics use the physics of fluid flow on the microscale scale; in the present a device, fluid samples are directed through micro-sized channels with specific geometries that cause the various cells to separate into distinct streams due to their different sizes. This integrated device takes advantage of the precise cell sorting capability of the iMF component and the rapid purification capability of the LCAT component to achieve higher quality cell isolation from complex mixtures compared to standard methods.



20µm-diameter beads separate from whole blood due to inertial forces (RBC = red blood cells). 20µm-diameter beads get trapped in the microvortices of LCAT as they pass through the main flow channel.

Image credit: Nivedita Nivedita, Neha Garg, Prithviraj Mukherjee, Willy Feng, Abraham Lee, Ian Papautsky, "Integrated Microfluidic System for Rare Cell Separation and Enrichment" 19th International Conference on Miniaturized Systems for Chemistry and Life Sciences (MicroTAS 2015), Gyeongju, Korea, October 25 - 29, 2015.

Copyrighted by the Chemical and Biological Microsystems Society (CBMS).

## Center for Advanced Design and Manufacturing of Integrated Microfluidics (CADMIM)

This integrated microfluidic device has the potential to achieve improved target cell purity and allows users to analyze complex samples like whole blood or untreated water. The device is being fabricated using scalable production methods such that transfer to industry is more straightforward. So far, results demonstrate the feasibility of the approach using model systems and indicate that the developed approach will also work with actual samples (such as whole blood).

The advantage of the developed microfluidic platform lies in its simplicity. The instant the untreated sample makes a single pass through the device, both target cell isolation and active enrichment are complete, resulting in an automatically prepared sample with higher target cell purity than is currently attainable. This leads to quicker, more reliable results without the need for binding assays, labelling, sample recirculation, or further post-processing. It is this active, integrated enrichment process immediately following highly selective cell isolation, all in one lab-on-a-chip, that sets this method apart from all the others.

This device has the potential to make significant impacts in front-end sample preparation workflows for cancer diagnosis by dramatically reducing the duration of the target circulating tumor cell identification and enumeration process and increasing the reliability of these measurements. An end product based could be a handheld device to isolate tumor cells from patient blood. These cells can then be used to tailor the therapy and/or monitor therapy response. Even broader impacts can be anticipated to be realized as the developed technology is applied to other blood-based diseases (malaria, hepatitis, etc.) as well as other business sectors where target cells are present in complex fluid mixtures (such in environmental monitoring, agriculture, consumer products, and forensics).

By using microfluidic technology, the resulting device becomes a miniature lab-on-a-chip amenable to mass production. Thus, this highly capable device will facilitate portable use - i.e., at the patient bedside (in the home or hospital) or anywhere point-of diagnosis is required (factory, beach, farm, crime scene, etc.)

**Economic impact:** To date this work has not yet generated direct economic impact because the team has so far only completed the initial feasibility and proof-of-concept. However, we probably would have not been able to conduct this early phase basic research on our own, mainly because of lack of knowledge and experience with microfluidic chip development. Therefore, this work indirectly saved the equivalent of the R&D costs for this project because it was done at CADMIM rather than at our company.

In general, the global cancer diagnostics market is expected to reach roughly \$13.1 Billion by 2020 with a compound annual growth rate (CAGR) of 12.9% from 2015 to 2020. Circulating tumor cells have emerged as the premier biomarker for cancer. Furthermore, since these cells travel through the bloodstream, the demand for liquid biopsies has grown tremendously. Highly invasive, costly, traditional tissue biopsies will only reveal genetic information (i.e., DNA) in one part of the tumor. However, tumor cells die routinely just like other cells and enter the bloodstream. Thus, blood contains DNA from all over the tumor, and acquiring measurements from blood is more informative and much less invasive compared to tissue.

As liquid biopsies become more sophisticated and capable of ultra-sensitive molecular readouts, their applicability to cancer diagnosis (as well as other diseases) is expected to rise dramatically. In fact, it is estimated that by 2029, the total annual market for liquid biopsies could be ~\$12B in the U.S. alone. The integrated microfluidic device described here would feed directly into these markets.

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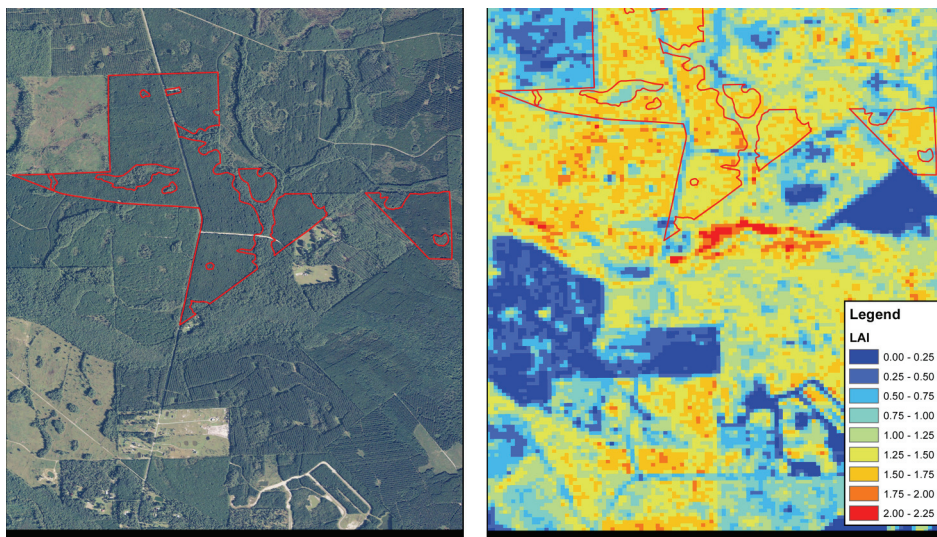
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## Remote Sensing for Diagnosing Nutritional Status of Forest Plantations

Over the years, on-site computations of Leaf Area Index (LAI) have been demonstrated to be the best indicators of the nutritional status of pine forest plantations and of whether they will require fertilization to achieve maximum productivity and value. Researchers at the Center for Advanced Forest Studies (CAFS) have developed techniques that use LANDSAT imagery to remotely estimate the leaf area index.



*This image shows the leaf area index in loblolly pine plantations in Florida that were calculated using Landsat Imagery. Image provided by the Department of Forest Resources and Environmental Conservation, Virginia Tech.*



## Center for Advanced Forestry Systems (CAFS)

Prior to the development of this LANDSAT methodology, the only reliable way to determine leaf area index was to send field crews to visit plantations and make on-site field measurements. This was and remains very time-consuming and costly to do. That plus an obvious limitation of on-site LAI measurements has been that it can only examine small samples of the forestry stands of interest.

Satellite imagery provides a total, 100% examination of entire plantation/forest stands. One CAFS member company now collects satellite data on every one of its plantations (approximately 1.8 million acres). It calculates LAI on every plantation that is greater than 3 years old. They use it to more accurately determine the plantations that will require fertilization. This helps the firm reduce costly and wasteful fertilization of stands that will not respond to fertilization.

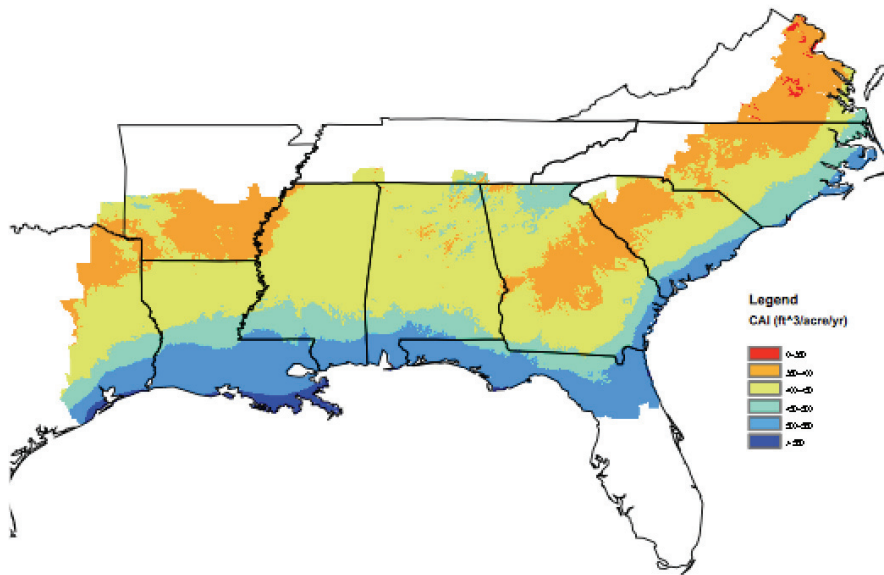
Too often, below average plantation responders to fertilizer applications are in stands that had good Leaf Area Indexes (LAIs). Taking advantage of this satellite-based LANDSAT-enhanced breakthrough, LAI technology can enable users to minimize or eliminate unnecessary fertilizing. The breakthrough has demonstrated that by using satellite enhanced LAI, average response to plantation fertilization can be maximized. With the addition of satellite-based Leaf Area Index (LAI) technology, this CAFS member company has become more capable of identifying and treating nutrient deficient stands and of better tracking the impact of fertilization applications on stands.

**Economic impact:** This CAFS research will help develop higher, more productive forest plantations that yield wood for eventual use in building materials, paper and bioenergy. Annual LAI assessments yield data that allows this firm to delay additional fertilizations and still maximize response; thus saving substantial amounts of unwarranted expenditures. Stands with low satellite LAI measurements are the ones then targeted in order to maximize responses to fertilizer applications. Fertilization is an expensive treatment (\$75-\$100 per acre) so postponing fertilization on stands until they will be responsive works out well economically and maximizes the response when dollars are spent. It is estimated that this CAFS sponsor alone has realized over \$1,000,000 in annual savings from reduced fertilization expenses. IF LAI becomes adopted nationwide, there is potential for an estimated \$18,000,000 in annual savings throughout the large pine forest plantation industry.

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## Forest Plantation Productivity Determination: A Process-Based Modeling

The process model Physiological Processes Predicting Growth (3-PG) was used to determine potential productivity of pine and Eucalyptus plantations in the U.S. and Latin America. 3PG is a dynamic, process-based model of forest growth developed by Landsberg and Waring in 1997. It runs on a monthly time step using species specific data on physiological processes combined with site specific data on climate and soil nutrient availability. CAFS's scientists working with the Forest Productivity Cooperative refined the model by incorporating new physiological parameters for commonly planted pine and eucalyptus species and developed a better method to estimate of soil fertility. They also assembled a detailed, spatially explicit database of the climate parameters needed for the United States, Argentina, Brazil, Chile, Colombia, Ecuador, Mexico, Uruguay, and Venezuela. With these data, they develop estimates of potential productivity of both pine and eucalyptus plantations for each country on a 1 km grid in a database accessible members of CAFS.



*Potential productivity of the Loblolly Pine in the southern United States determined using the process model 3PG. Potential growth rates are expressed as cubic feet of wood grown per acre per year in each region. Red and orange areas have lower potential productivity than blue areas. Image provided by CAFS.*

These breakthrough refinements improve the accuracy of estimating potential productivity of the most important forestry species in both North America and South America. This work with the 3-PG model significantly expanded the number of species and countries where estimates of potential forest productivity are available to members of CAFS to help guide decisions on forest investments. It represents a significant technological advancement that goes well beyond the previous state of technology. It provides increases

## Center for Advanced Forestry Systems (CAFS)

in flexibility, accuracy, precision and reliability that ultimately guide multi-million dollar investments in the forestry sector worldwide. Investors now have access to user-friendly estimates of the productivity of the forestry plantations under specific environmental conditions and how best to enhance stand growth and value.

Results using the updated 3-PG models and Geodatabases have demonstrated that the potential productivity of plantations in many areas of the Americas is much higher than previously thought. This increases opportunities for heretofore unattractive regions for timberland investment.

**Economic impact:** GreenWood Resources business model is focused on growing higher quality trees in a more cost-efficient than other timberland managers. GreenWood relies on accurate estimates of current and potential productivity of forest plantations to guide investments in timberland and evaluate potential financial returns. The work on 3PG by CAFS is a valuable tool that can be used to evaluate alternative investment decisions. The maps of potential forest productivity in different countries enables GreenWood Resources to match species to sites to maximize productivity for selected markets.

Improved estimates of potential productivity and growth increases possible through intensive silviculture of forest plantations is leading to better forest management decisions that increases the productivity, profitability and sustainability of forest management. GreenWood Resources has used these tools in Chile to identify lands of marginal agricultural quality that can be planted with improved hybrid poplar varieties to provide a renewable source of cellulosic bioenergy feedstock. GreenWood is using these results and is working to evaluate plantation options in several other regions of the U.S. and around the world.

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# Advanced Knowledge Enablement (CAKE)

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## Driver's Drowsiness Detection System

In this project, CAKE researchers at Florida Atlantic University developed a driver drowsiness detection system. This research combines smartphones with machine learning to detect driver drowsiness in real time. The system is based on visual input that includes the position of a driver's face and head/eye position.

This innovative algorithm combines software components for face detection, human skin color detection, and a classification algorithm for the eye state (open vs. closed). The system uses commercially available smart phones to monitor drivers. Visual inputs are then used to detect signs of drowsiness. When signs of drowsiness are detected the system issues an alert.

The system uses innovative machine learning algorithms that continuously monitor driver behavior and alerts the driver in real time when certain thresholds are met. The high speed algorithms provide continuous, real-time analyses of driver imagery without consuming an undue of battery power.

In order to capture a clear view of the driver's face the device is mounted securely and aimed precisely at a specific distance. Once mounted, the device begins a training process to determine the baseline head position and eye movement. After this calibration, real time monitoring begins, sending an alarm if the head dips or eyes close for prolonged periods; both can be indicators that the driver is falling asleep. The system has been demonstrated to be applicable in real time, easily portable to different platforms, highly accurate, and robust.

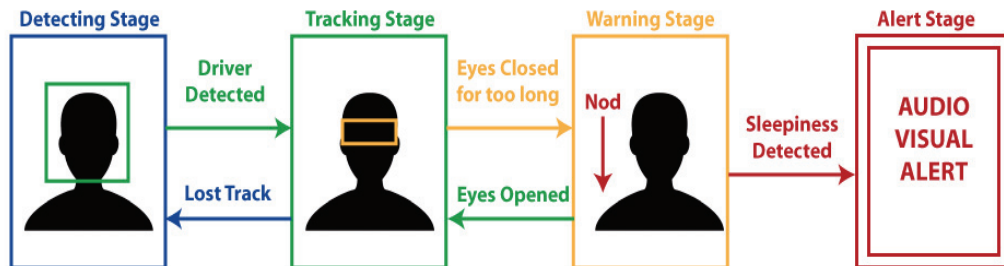


*A screenshot of the driver detection video. Image provided by CAKE.*

The advantage of being able to use the ubiquity of smartphones instead of relying on built-in products makes it feasible to deploy the system in any vehicle. With today's inexpensive infra-red cameras the device can operate in poor lighting conditions.

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The CAKE team has developed and tested the software prototype for Android smartphones. The next step is to port to iOS platform for iPhones. Soon the system will be commercialized as a general smartphone application. Soon an embedded system with an infra-red camera will be completed. It will use the same algorithms so it can be mounted on the car's dashboard. These two systems, one using smartphones and another using a device, will be universally-applicable to all cars, and at very low cost. Eventually, the systems can be built in into newly manufactured cars.



*The four stages of the Drowsiness Detection System. Image provided by CAKE.*

With the high rates of accidents caused by drowsy drivers the need for these products is obvious. Beyond passenger vehicles, drowsiness alert systems can be expected to be applicable to public transportation modalities because taxis, buses, trains, subways, and long-haul truckers all face the same risks from driving drowsy. Adoption in these sectors could be driven by regulatory agencies as part of safety requirements.

**Economic impact:** There is significant statistical evidence that there is a commercial need for driver drowsiness detectors. There are alarming numbers of road accidents. Worldwide, over a million people die on the road every year with 6% being linked to driver drowsiness. It has been estimated that nearly 75,000 deaths could be avoided by alerting drivers, either startling them awake, or indicating that they should pull over and sleep instead of continuing to endanger themselves or other on the road. Though almost impossible to estimate precisely, the economic impact of driver drowsiness detection algorithms and related products substantial.

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## Modeling Ebola Spread Using Big Data Analytics

A model of Ebola spread was developed using innovative big data analytics techniques and tools. Massive amounts of data were used from various sources including Twitter feeds, Facebook and Google. This data was then fed into a decision support system. It models the spread pattern of the Ebola virus and creates dynamic graphs and predictive diffusion models based on the outcome and impact on either a specific person or on entire communities.

This CAKE research created computational spread models for Ebola that will potentially lead to more precise forward predictions of disease propagation. The tool will help identify individuals who are possibly already infected. It is capable of performing trace-back analysis to locate the possible sources of infection for particular social groups. Working with Florida International University researchers and other partner universities, the Florida Atlantic University research team also collaborated with LexisNexis Risk Solutions (LN); a leading big data company and CAKE member. LN provided large amounts of data about relationships among people in the United States. Researchers used data analytics and tools to model disease spread patterns. The project performed modeling, analytics, and development of a Decision Support System (DSS), that calculates probabilistic outcomes of Ebola impact on either specific persons or communities at a specific locations. This information is then fed to FIU's Terafly system for geospatial mapping and other services.

Jointly with the LN research team, people clusters were created based on proximity and a model using weighted scores was built to approximate physical contacts. In creating people clusters, researchers used public record graphs to calculate distances between an affected person and his/her relatives and friends. Based on this model, the disease propagation paths were developed.

As part of this research, the NewsCubeSum was developed. This is a personalized multidimensional news update summarization system. It collects data from news articles and Twitter. The system utilizes OLAP (OnLine Analytical Processing) and supervised sentence selection techniques to generate brief summaries. It delivers news summaries in multiple dimensions, such as time, entity, and topic. This project demonstrated how this system can be used in improving situational awareness during disease outbreaks.

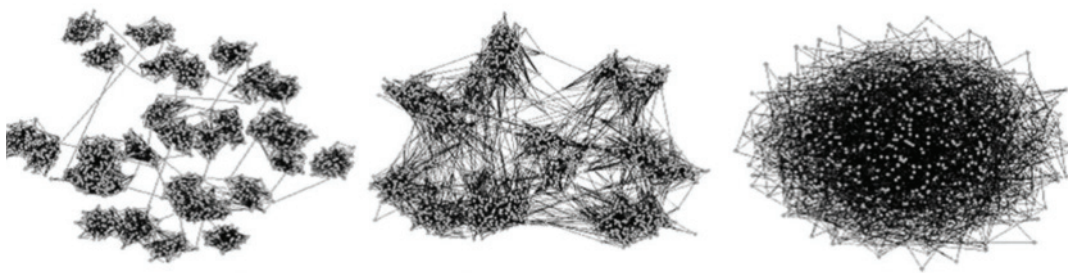
Tracking and containing Ebola requires enormous resources. This system provides a proactive approach to reasonably reduce the risk of exposure of Ebola spread within a community or a geographic location. This work represents an improvement over previous state-of-the-art, because it used innovative data analytics techniques and the latest HPCC Systems technology to developed models of Ebola spread. With information from multiple sources indicating infected individuals and their personal relationships and social groups, dynamic graphs can be created, and predictive diffusion models can be used to study key issues of Ebola epidemics, e.g., location, time and number of expected new cases. The two fundamental diffusion models are Independent Cascade Model (IC) and Linear Threshold Model (LT). Both models follow an iterative diffusion process wherein infected nodes infect their uninfected neighbors with certain predictable probabilities. Based on fundamental models, advanced propagation models were developed to estimate an influence function by examining past and newly infected notes and predict subsequent infections.

The DSS allows the individual to enter their specific information through a Web-application such as travel information. The mobile interface application would automatically extract the geo-coordinates of the individuals. This would allow the system to intelligently query the movement of the person and a possible con-

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tact in the areas affected by Ebola or in the areas affected by Ebola. For instance, if found that a person affected with Ebola was in a theater the previous evening, then a monitoring alert could be issued to the other people within the theater to take extract precaution and watch any sign of Ebola impact such as fever or headache.

The mobile interface will further allow the people to enter the signs of Ebola such as fever specifically above 100.4°, chills, headache and vomiting, myalgia, intense weakness. While these signs are very common with other diseases as well, such as Malaria and Typhoid, laying over these impacts on the geo-coordinates of having the person in a geographic proximity of a person in a community with impact of Ebola, will provide more focused results with higher accuracy.



*Social network analysis types showing increasing risks of Ebola propagation. Image provided by CAKE.*

The DSS will also interface with the social groups of the person. This allows the extraction of relationship maps to predict the higher probability of Ebola spread within specific communities. The social group integration such as a LinkedIn or a Facebook application programmable interface (API) can extract such data very accurately thereby providing high precision and accuracy in risk prediction.

**Economic impact:** The proposed methodology, including coalition-building efforts, supports solutions to a wide range of other public health issues. The economic impacts can be tremendous by predicting outbreaks of the deadly Ebola virus (or any other epidemics) and directing potential victims to the nearest suitable medical facility. This research can also help in indicating the areas in which new facilities should be opened, where disease outbreaks are beginning to occur, and how they are likely to expend.

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## Smart Building Optimization Systems

The ongoing development of smart buildings has recently gained in importance at Florida Atlantic University. Innovative methods are being used to optimize the operation of buildings and thereby reduce operating expenses and reduce energy consumption. In this project, research was conducted on the FAU's new LEED Platinum-certified Engineering building that houses the Center for Advanced Knowledge Enablement's (CAKE's) laboratories. The building was designed both as a model of how new technologies can drastically decrease the energy requirements of a large building and as a "living laboratory," so that students and faculty can actually see how these systems work and interrelate. The building is equipped with hundreds of sensors that measure and collect various parameters and display them in real-time on a dashboard, which is accessible through a Web-based application called DeviseWise from ILS Technology, a member of our I/UCRC and our partner in this project.



*Mechanical equipment, pumps, piping, and sensors are part of the building HVAC systems. Image provided by CAKE.*

During 2014-15 the CAKE team developed a data warehouse that stores information from several different sensor systems including DeviseWise, standalone wireless and wired sensors, PDM calculated clusters, and weather stations. The collected weather data comes from a link to the WeatherBug API. Every 15 minutes it pulls meteorological information including temperature, humidity, wind speed and direction, air pressure, rain amount and light levels. The system provides tools for extracting and analyzing sensor data. It exports it in a variety of formats for use by other tools such as the Weka Machine Learning Suite and Excel.

As part of the NSF Center project, FAU faculty and students worked with Aware Technologies and their Process Data Monitor (PDM) system. This is an alerting system that uses data mining techniques to categorize sensor data into similar clusters of information. It automatically detects when a current cluster is outside of normal operating parameters. It then reports anomalies to an operator.

Researchers have analyzed the efficiency of the building's solar panels by tracking the power generated over a one-year period. They noticed high variations in the amount of solar power generated. This was mainly attributable to variable day-by-day cloud coverage. Between March and May 2012 there were very clear skies with almost no rain and hardly any clouds. Conversely, the beginning of 2013 witnessed a



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period of high cloud coverage combined with shorter days. This caused reduced solar energy generation. Currently, the building's solar energy production is on average 4.45% of the total energy used by building systems.



*Solar photovoltaic cells on a building roof for power generation. Image provided by CAKE.*

**Advantages over previous methodologies:** This work presents an excellent example how researchers are using the new Platinum-certified building and FAU labs as a "living laboratory" in order to better understand and conduct research in the areas of smart building technologies and optimization. The main focus is on improving energy efficiency; however the other components of the project include sustainability, water savings, material and resource selection, and indoor environmental quality.

The end-user systems can be summarized as: 1) Alerting and monitoring systems that analyze data from various sensors in the building to issue alerts when anomalies are detected, and; 2) A data warehouse system that collects and stores data from the sensor systems. Data can then be used for determining correlations between photovoltaic energy generation and weather conditions, and calculation of energy flow between the different components of the air conditioning systems.

**Economic impact:** Strong instrumentation in the new LEED Platinum engineering building opens up a multidimensional view of the inner working of its HVAC and power systems. A variety of sensors allow detailed analyses of the building system performance and the data center power consumption. This research provides the foundation for analyzing and improving energy efficiency in buildings equipped with sensors and solar panels. The results of this research are being used to analyze and improve the operation of new "smart" buildings.

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## Machine Learning Algorithms on HPCC/ECL Platform

The FAU's Center for Advanced Knowledge Enablement (CAKE) developed a wide range of machine learning algorithms on the High Performance Cluster Computing (HPCC) platform. This platform includes traditional algorithms such as Naïve Bayes and K-Nearest Neighbors, to more advanced techniques such as Deep Learning. This enables researchers and practitioners to apply machine learning algorithms on big data to extract patterns and perform predictive tasks. The HPCC architecture, written in conjunction with the ECL programming language, is LexisNexis's answer to applying machine learning methods on big data.

HPCC provides a platform for implementing parallel, distributed, and scalable machine learning algorithms. The general linear algebra and statistical operations implemented in HPCC along with the data structures provide an ideal platform for implementing the machine learning algorithms.



*Machine learning algorithms using the vastly increasing volumes of personal, wearable health information to anticipate health risks and concerns given the user's historical and present lifestyle information. Image credit: Fitbit.*

The amount of data produced from bioinformatics to social media to web documents, has exploded in recent years. Many traditional approaches fail when dealing with terabyte, petabyte, or larger datasets preventing consumers from fully benefiting from their data. Analyzing these large amounts of so-called big data opens up new research areas that were not possible 20 years ago. Major companies such as Google, Facebook, Twitter, and Amazon would be less effective without taking advantage of big data analytics. Big data analysis demands large-scale systems to both manage and process huge quantities of data. Big data

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with characteristics such as high volume, high complexity, and data heterogeneity require new ways of thinking and new paradigms for knowledge extraction.

This breakthrough is an improvement over more traditional analytics which rely heavily on human analysts. The sheer volumes of data that have high amounts of potential correlations and hidden patterns do not allow for comprehensive analysis using traditional data analytic tools. Machine learning and big data tools overcome these problems by leveraging properties intrinsic to the data to infer semantics and formats, deriving effective and general algorithms for data processing and analytics.

In comparison to traditional analytics, machine learning delivers the promise of extracting patterns in an automated fashion with far less reliance on human supervision. The methods are data driven. They thrive on and benefit from increased data because with more information, more can be learned. Given the limitations of human comprehension in the face of truly massive amounts of data, machine learning is able to discover hidden patterns on very large-scales.

End users/consumers receive multiple advantages from applying machine learning using big data to do many different kinds of predictive tasks. These are in various domains ranging from fraud detection and product recommendations to energy load forecasting to healthcare predictions. Example end-user products include: 1) Machine learning algorithms using the vastly increasing volumes of personal, wearable health information, via devices such as FitBit, to anticipate health risks and concerns given the user's historical and present lifestyle information; 2) HPCC big data processing and machine learning methods to analyze crime patterns to anticipate specific areas likely to have near term criminal activities and to adjust police resources accordingly; 3) Frameworks to collect and analyze historical and real-time power plant information to predict site-wide and individual component failures producing warnings and predictive work orders mitigating costs due to failures and equipment replacement, and; Analytics based on energy smart grid network data to optimize electrical loads and to anticipate specific failure points in order to avoid loss of service by fixing issues remotely or by dispatching crews prior to anticipated failures.

**Economic impact:** Machine learning provides reliable and accurate predictions for a wide range of domains. Fraud detection and prevention has contributed to billions of dollars in recovered funds. In 2013, the IRS prevented or recovered \$24.2 billion related to identity theft fraud. Predicting shopping patterns can allow stores to better anticipate customer needs and increase overall sales revenue; thus shifting the customer interaction paradigm from a mostly reactive process into a more proactive one wherein systems predict consumer needs and offer optimized services and products. Predicting diseases can reduce burdens on healthcare. Cyber security is critical for national security. Big data and machine learning approaches work synergistically to anticipate and prevent costly attacks. The HPCC architecture provides an established compute resource where big data and machine learning go hand-in-hand without new or additional development and storage costs. The use of ECL to implement the machine learning algorithms allows for better. Since the ECL language is automatically compiled into C++, a more traditional imperative/procedural lower level language, it's easier to measure efficiency gains by comparing the number of lines of code between those lines of code manually written in ECL versus lines of C++ code that are automatically generated by the same ECL codebase. This ratio is roughly 100/1, indicating two orders of magnitude improvements in coding efficiency by leveraging the higher level declarative dataflow paradigm that ECL offers.

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## Modeling Sea Surge and Flooding using ALTA and TerraFly

The TerraFly team at the NSF I/UCRC CAKE at Florida International University, CAKE's member ALTA (Autonomous Lighter Than Air) Systems, Inc., and the SeaRobotics Corporation are producing smart balloons tethered to small unmanned vessels to collect environmental data. In combination with the geospatial data already served by TerraFly, continuing work on this breakthrough has the potential to transform the modeling of sea surges and flooding.

TerraFly (<http://TerraFly.com>) is a technology and tool set for fusion, visualization and querying of geospatial data. The visualization component of the system provides users with the experience of virtual "flight" over maps comprised of aerial and satellite imagery overlaid with geo-referenced data. Autonomous Lighter Than Air was invented by John Ciampa, the inventor and founder of Pictometry. The ALTA invention has been awarded three U.S. Patents. ALTA has sponsored research at FIU at about \$1 million. SeaRobotics Corporation, located in Stuart, Florida, specializes in marine robotics. SeaRobotics Unmanned Surface Vehicles (USVs) are used worldwide by government organizations, academia, commercial survey companies, and others.



*TerALTA balloon oblique multispectral aerial image, vegetation index in reddish color, derived nearshore sea depths and isobaths for NSF IUCRC Compendium CAKE-MSS Modeling Sea Surge and Flooding using ALTA and TerraFly. Image provided by CAKE.*



## Advanced Knowledge Enablement (CAKE)

This work represents an improvement over previous state-of-the-art because the addition of an aerial imaging and communication source provides valuable new sensing capabilities. The collection of sea depths near the shore has eluded traditional collection platforms such as LIDAR and aircraft-based aerial photography. The unmanned shallow draft vessel and the low altitude balloon aerial platform are uniquely suited to this task. The TerraFly system allows users to fuse and explore multi-source geospatial data. Examples of fusing ALTA oblique imagery with core geospatial data are at <http://Teralta.com>.



*TerALTA balloon-mounted bathymetry sensor operated via a robotic vessel for NSF IUCRC Compendium CAKE-MSS Modeling Sea Surge and Flooding using ALTA and TerraFly. Image provided by CAKE.*

The project is expected to result in a packaged product that would enable users to collect data in areas that are presently hard to access and to then immediately analyze them via the TerraFly system. Service packages capable of data collection, storage, and analysis are also possible for end-users who may then desire to periodically collect data or who have interest in particular locations at particular times.

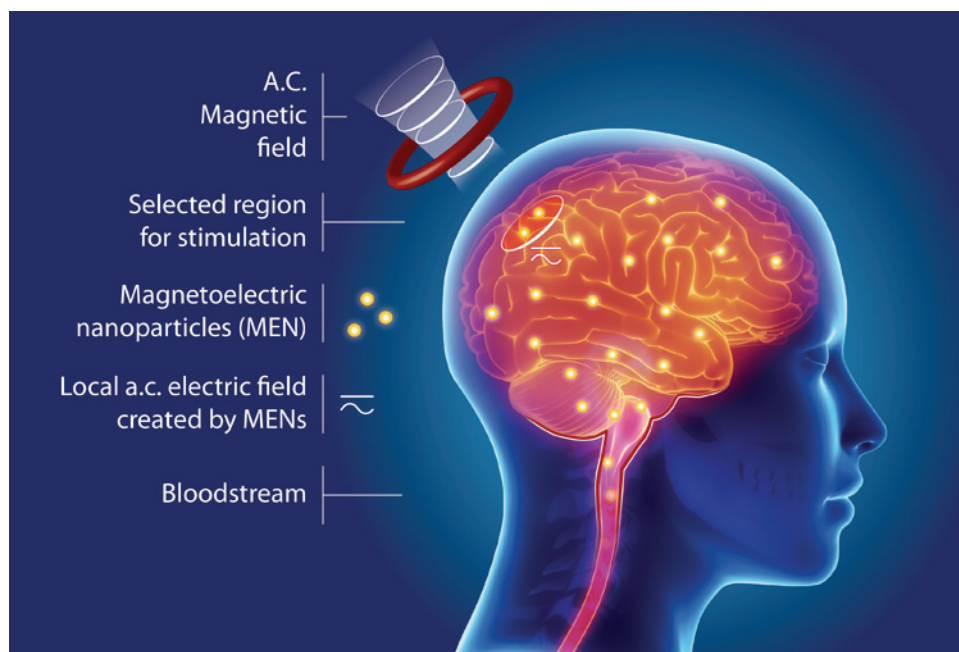
**Economic impact:** With the help of FIU's TerraFly technology, ALTA opens a new multi-billion market for aerial photography. This is because it produces images of much higher resolution than are possible using other technologies. Image collection is currently accomplished from ground-based cameras, aircraft, and satellites. ALTA is higher than a ship-based camera and therefore sees more. ALTA is lower than an aircraft and therefore sees better. Additionally, compared to other aerial platforms ALTA has low cost components. For the capital outlay of one manned aircraft, hundreds of ALTAs can be deployed. Additionally, balloons are dramatically cheaper than drones. ALTA missions eliminate cost of pilots, aircraft, and airports. Costs of operation are a fraction of those of other aerial collection platforms. Moreover, ALTA can be deployed in minutes and have information and images returned instantaneously. The ALTA technology is thus poised to produce much higher-quality imagery at much lower cost than current technologies, thus opening up new markets and bringing new capabilities to existing markets such as public safety, real estate, construction, environmental monitoring, disaster mitigation and disaster recovery.

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## Wireless Deep-Brain Stimulation With Magnetoelectric Nanoparticles

The brain is a complex bio-electric circuit made of billions of neurons that are inter-connected through chemical and electrical synapses. The ability to remotely stimulate selective neurons deep in the brain remains a major challenge. Overcoming it will enable highly personalized "pin-point" treatments for neuro-degenerative diseases such as Parkinson's and Alzheimer's Diseases, Essential Tremor (ET), Epilepsy, and others. Furthermore, by the law of reciprocity, this nanotechnology can pave a way for reverse-brain engineering.

This FIU team has invented and patented a technology (S. Khizroev and M. Nair, "Wireless brain stimulation," U.S. Patent application 13/900,305, filed 05/22/2013, granted 01/26/2016) to answer the above challenge by using a novel class of multifunctional nanoparticles known as magnetoelectric nanoparticles (MENs). Because of MENs capability to couple magnetic and electric fields at the sub-neuronal level, they enable a unique way to combine the advantages of both the high efficacy stimulation by the electric fields and the external-control capability of the magnetic fields. They therefore open a novel pathway to control the brain.



*Wireless deep-brain stimulation with Magnetoelectric Nanoparticles administrated into the brain via an IV injection. Image provided by CAKE.*

This study, conducted on mice, demonstrated for the first time the feasibility of using MENs as externally controlled "smart" nanoparticles for wireless navigation and selective control of specific functions deep in

the brain. The paper recently published by FIU investigators has been selected in the list of 100 Top Science and Technology Stories of the Year (2016) by *Discover Magazine* (January 2016 issue) [R. Guduru, P. Liang, J. Hong, A. Rodzinski, A. Hadjikhani, J. Horstmyer, E. Levister, and S. Khizroev, "Magnetoelectric spin on stimulating the brain," *Nanomedicine* (London) 10 (13), 2051-2061 (2015)]. On behalf of FIU, the team has put together several multi-million-dollar research proposals on the subject.

This breakthrough study represents an important milestone in deep-brain stimulation because it provides a wireless and non-invasive way to achieve significant results. Current DBS technology is operated at macro-scale and often relies on highly-invasive direct-contact-electrode techniques. Current non-invasive brain stimulation methods include rTMS and tDCS, but in both the depth and locality of focus are strongly limited. FIU's technology, using MENs, overcomes the current technology's roadblocks.

The completed study is a stepping stone towards the development of a precision nanotechnology for simultaneously achieving the following three important functions: 1) stimulation; 2) release of drug(s) and other macromolecule(s), e.g., peptides, RNAs, and others, in selective brain regions via remote control, and; 3) mapping the electric field due to neural activity. Achieving each of these functions would be important milestones on their own. Achieving all these three functions simultaneously may very well present a pathway to next-generation pinpoint treatment of neurological diseases.

In the near-term future, a main end-user product would be an advanced wireless deep-brain stimulation (DBS) technology for treating patients with Parkinson's Disease, Essential Tremor, Alzheimer's Disease, Autism, and other neurological diseases.

Even more far-reaching applications might be envisioned when biodegradable MENs will be developed in the future. This is definitely within reach due to the recent development in the emerging field of carbon based nanotechnology. Potential applications span from the prevention and treatment of neurodegenerative disorders to opening pathways to significantly improving fundamental understandings of the brain and to reverse-engineering the brain.

**Economic impact:** According to the 2011 technology assessment by experts at California Institute of Technology, the deep-brain stimulation (DBS) market was around \$360 million. Conservative projections indicate that the technology can impact the multi-billion-dollar medical and information processing market segments.

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# Advanced Vehicle and Extreme Environment Electronics (CAVE<sup>3</sup>)

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## Tools to Ascertain Survivability and Prediction of Damage to Electronic Systems under High-G Shock at High Temperature

Electronics are transitioning to thinner form-factors. These are being used in extreme environments placing the components in ever increasing proximity to the external interfaces of the products and subjected to high temperature, mechanical shock and vibration. In many situations the loads may be significantly more severe than those encountered in consumer electronics.



*Electronics in unmanned space missions can be subjected to the high-g stresses of launch, an issue addressed by this technology breakthrough. Credit: NASA/Bill Ingalls*

In extreme applications electronics may be stored for a prolonged period of time prior to first use. The challenge of electronics survivability is even more daunting considering the fact that extreme environment applications such as automotive electronics or military electronics require high reliability for mission assuredness. High reliability is generally assured using accelerated tests, a process which is fairly time consuming and iterative. Part replacement in electronic systems is typically done on a timed basis to ensure safe reliable operation.

## Advanced Vehicle and Extreme Environment Electronics (CAVE3)

In order to address deficiencies in the state of art, the CAVE<sup>3</sup> research team developed advanced, multi-scale modeling methods and high-speed experimentation test protocols for analyzing system-level shock survivability of electronic products. Leading indicators of failure were developed for assessing accrued electronics damage during sustained high-g/high-temperature operation. The indicators allow for early assessment of system condition and for condition based maintenance of systems to ensure more reliable operation. The team's leading indicators for prognostics during high-g operation at high temperature have made possible assessment of damage states in operational systems. Contributions include resistance spectroscopy methods, feature extraction and classification methods for second-level interconnects, and methods for assessment of remaining useful life. The modeling methods and test protocols have made it possible to assess system-level shock loads and their impacts on interconnects at the package- and chip-levels.

The technical breakthrough of multi-scale methods for high-g shock assessment and leading indicator based prognostic health management allows for the following advantages: 1) Elimination of excessive accelerated testing for assessment of shock survivability of electronic systems; 2) Improved ability to design more reliable harsh environment electronic systems while using the latest consumer electronics components which may not have been originally designed for use in extreme applications; 3) Improved ability to determine damage states and remaining useful life in field deployed electronic systems without taking them out of operation, and; 4) Enhanced ability to perform repairs and replacements based on system condition thus allowing for meaningful intervention in the repair cycle prior to catastrophic failure.

The breakthrough has implications for a number of applications relevant to harsh environment electronics including: 1) Electronics in unmanned space missions which can be subjected to the high-g stresses of launch, atmospheric re-entry and landing often at high temperature or low temperature; 2) Electronics in missile fuzing applications may be subjected to 100,000g in hard target impact with a requirement to function throughout the event; 3) Automotive underhood electronics which are subjected to simultaneous temperature and vibration challenges with the expectation of reliable operation; 4) Defense electronics may be in storage for longer periods of time prior to deployment in high-g applications, and; 5) Electronics in downhole drilling applications may be subjected to high-g forces in addition to high temperatures.

**Economic impact:** Health management system implementation in Automotive and Aerospace are currently limited to on-board diagnostics and reporting of diagnostic trouble codes. Economic impacts of this breakthrough work include: 1) Reductions in cycle-time for development of shock survivable electronic assemblies, reductions in product development cost, and in the number of iterations needed for design optimization; 2) Better foundations for development of new products for prognostic health management of electronic systems and assessment of remaining useful life; 3) Lowered risks associated with the deployment of new technologies through insight into accrued damage and system states; 4) More opportunities in workforce development for jobs in the assessment of the damage-state of electronic assemblies for intervention through repair and replacement.

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# Child Injury Prevention Studies (CChIPS)

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## Comparing FMVSS 213 Sled Test to the Full-Scale Vehicle Crash Environment

The objective of this work has been to evaluate the fidelity of the Federal Motor Vehicle Safety Standard (FMVSS) 213 sled test for testing child restraint systems to current vehicle crash tests. To do this, Maltese et al. reviewed over 1200 NHTSA vehicle frontal crash tests and evaluated pulse characteristics such as the length of the pulse, maximum acceleration, time at maximum acceleration, maximum velocity, and rise rate (max acc/time at max acc). These characteristics were then compared to FMVSS 213. It was known that the FMVSS 213 pulse onset rate and maximum acceleration were similar to that of light trucks, SUVs, and small school buses - none of which are typical family vehicles.



*A child in a restraint system. Credit: iStock*

## Child Injury Prevention Studies (CChIPS)

CChIPs researchers demonstrated that the maximum acceleration of the FMVSS 213 test is similar to a sedan or minivan in a 25 mph full frontal rigid barrier crash test or a 35 mph offset deformable barrier crash test. The FMVSS 213 rise rate is similar to a SUV or pickup truck in a 35 mph offset deformable barrier crash test. The researchers also demonstrated that forward-facing child restraints significantly reduce pediatric injury risk compared to vehicle 2 belts alone. Therefore, it is not clearer that in order to properly assess the efficacy of child restraint systems, they need to be tested in crash environments similar to current vehicles.

Advantages over previous methodologies: The current regulatory standard for child restraint systems, FMVSS 213, is over 30 years old. While it was known in the industry that the protocol was outdated and not representative of the modern-day vehicle fleet in geometry or stiffness, there were no studies that illuminated these disparities. Therefore, this CChIPS work provided much needed scientific evidence to support the development of a child seat crash test protocol that deviated from FMVSS 213.

The end-user product/processes ramifications are numerous. In April 2014, Consumer Reports launched its new child seat crash test protocol that implemented the Maltese et al research findings. The new protocol implemented a frontal crash pulse that differed from FMVSS 213 in maximum acceleration, onset rate, and maximum velocity but more closely replicated the averages for those attributes as summarized from the study. These pulse characteristics were chosen to better represent the current vehicle fleet crash testing.

**Economic impact:** Use of the results of the Maltese study team eliminates the need for Consumer Reports (CR) to independently analyze actual crash data or to conduct its own crash tests to determine crash attributes for duplication. It is estimated that approximately \$350,000 was saved by CR in utilizing the results of the study.

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# Ceramics Composites and Optical Materials Center (CCOMC)

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## More Economical Bullet Proof Glass Materials: Crystallization of Magnesium Aluminate Spinel

Magnesium aluminate spinel ( $\text{MgAl}_2\text{O}_4$ ) is a transparent material that has exceptional ballistic protection performance. The ballistic properties of spinel match those of current laminated glass except this material enables a 2-fold thickness reduction of the transparencies in Humvees. The weight savings reduce fuel consumption, lightens doors, creates more interior space and makes vehicles easier to maneuver. In addition, spinel transparencies can be used in phones, tablets and laptop computers. Furthermore, its transparency enables new types of laser materials and windows for IR lasers and detectors. When transparency is not critical, spinel can be used as a refractory in high temperature furnaces.



*Improved bulletproof glass is one application of this technology. Credit: iStock*

Three technical barriers prevent spinel from realizing this full commercial potential. First, the need to use high-temperature high-pressure densification methods adds tremendous cost to the manufacturing cost of a transparency. Second, manufacturing spinel powder is costly. This is partly because only one commercial manufacturer produces powder suitable for making transparencies. The third barrier arises because the manufacturer uses high temperature processes to make the spinel phase by either melt or solid-state reac-

## Ceramics Composites and Optical Materials Center (CCOMC)

tions in a high purity production facility. The coarse-grained product is then milled to a particle size suitable for the high temperature-pressure densification step.

It is well known among ceramic engineers that having a smaller particle size and uniform morphology enable reductions in the temperatures and pressures required to make fully dense ceramics that are transparent. To address this challenge, the NSF sponsored Ceramic, Composite, and Optical Materials Center, CCOMC, an I/UCRC at the Department of Materials Science & Engineering at Rutgers University has developed a breakthrough low energy rapid hydrothermal synthesis route for the production of spinel powder.

The process uses inexpensive raw materials similar to those used in traditional high temperature reactions. The overall process-energy requirements are lower than other spinel synthesis techniques. The resulting high purity powder consists of uniform submicron particles that are ideal for transparencies.

The researchers, Daniel Kopp and Richard Riman credit their success to the predictive power of thermodynamics, since it was able to explain why prior attempts to develop a hydrothermal method failed and clearly defined what they had to do to invent a successful process. This new process has also been used to make 10 other new ceramic materials.

**Economic impact:** This new process has the potential to greatly reduce the cost of spinel powder for several reasons. First, less expensive raw-materials can be used. Second, the reaction conditions employ low temperature and times that are short relative to the current commercial process. Third, the powder does not need any energy intensive milling because sizes and morphologies are controlled by the hydrothermal process. Finally, the capital cost of the reactor is small compared to the capital cost of high temperature furnaces and mills that are currently used to manufacture spinel. Densification of the powder to a transparent state is easier and can be more reliably achieved. This is because the powder has a submicron particle size.

The above benefits collectively allow for a 2- to 5-fold reduction in spinel manufacturing costs. This allows spinel to be an economically viable alternative to laminated- or ion-exchanged-glass for ballistic and display applications, respectively.

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# Center for the Design of Analog-Digital Integrated Circuits (CDADIC)

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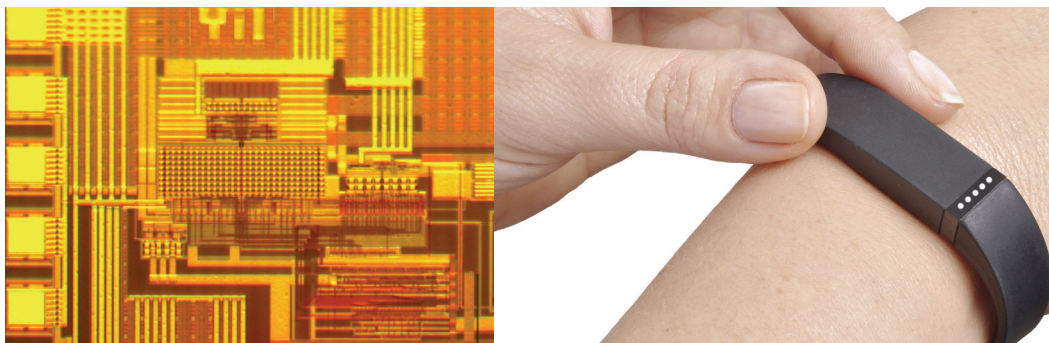
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## Incremental Analog-to-Digital Data Converters

Wearable devices are crucial to the Internet of Things (IoT), with more than 35 million connected wearable devices in use at the end of 2014. In wearable devices and other IoT applications, integrated sensor interface circuits are required to prepare the analog sensor output for digital signal processing. In some cases, such as image sensors and electroencephalograms (EEG), a single interface needs to be shared among many sensors. Often the sensors operate in battery-powered devices, and hence power dissipation in the interface circuitry is of great concern. The interfaces usually require high-accuracy ultra-low-power analog-to-digital converters (ADCs) with low signal bandwidth.

Incremental analog-to-digital converters (IADCs) represent an excellent choice for use in such sensor interfaces. They apply a combination of signal processing and noise shaping to achieve high accuracy. Their sample-by-sample operation allows sharing a single ADC among multiple sensors.



*A potential application of the incremental ADC in a wearable device, and its integrated hardware implementation. Image on left provided by CDADIC. Image on right from iStock.*

CDADIC researchers have developed novel IADC architectures that achieved both high accuracy and excellent power efficiency. A particularly useful new IADC configuration was recently found, which reuses a single active component multiple times. This breakthrough hardware recycling technique extends the accuracy of the converter with very low power consumption. Compared to the conventional single-step IADC of the same accuracy, the new ADC reduces the power requirement by a factor of close to 1000.

Fabricated on an integrated chip, the novel device demonstrated superior performance. It offers a power-efficient realization for various integrated sensor interfaces used in industrial, medical and environmental applications.



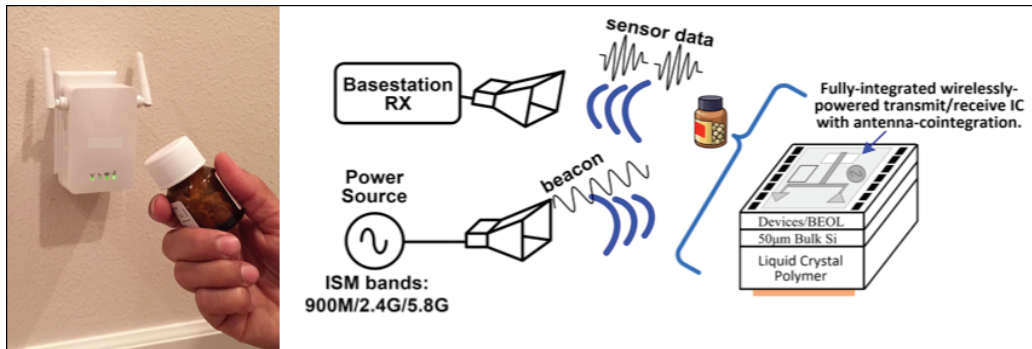
**Economic impact:** The next big wave of data-driven technological innovation will connect physical devices embedded with tiny computing devices to the Internet. This will help advance wearable electronic systems and smart appliances in homes and offices. These have the potential to greatly improve the efficiency and safety of daily activities. As a result, it is predicted that there will be a rapidly growing market for sensor and micro-actuator interface devices, which require micro-power high-accuracy ADCs as their key components. The data converters developed under the proposed research will play important roles in such interfaces. There is considerable interest by high-technology companies in this work, as shown by grants and gifts received from several CDADIC companies (and many outside ones) to support more research in this field. Incremental analog-to-digital converters have been receiving attention in the many applications. They allow the translation of analog signals into digital form in a sample-by-sample manner, and are able to achieve high accuracy just like noise-shaping converters.

Since these converters can be multiplexed among many sensor channels, and require minimal amount of power using our hardware recycling technique, they represent excellent choices for wearable devices. The total number of connected devices in which our circuits may be used - including smart home appliances, "wearables," smart metering systems, robots and autonomous vehicles. These are projected to grow to tens of billion by 2019. The integrated circuit industry will benefit from innovations in this field. The country will benefit by maintaining our global competitive advantage in the digital economy.

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## RF-energy Harvested mm-Wave SoC for mm-Wave RFID

The Internet-of-Everything (IoE) envisions a connected world with multibillions of sensors that communicate through the Internet, providing real-time information that guides decisions. IoE is projected to be a key driver of the global economy with overall market size projected to reach \$1.7T by 2020. A key limitation to realizing this vision of a fully-sensed and networked world is the development of the sensors itself. An ideal sensor must be physically tiny, have almost infinite battery life, be able to wirelessly communicate with the networks. All of this must achieve this at costs that are compatible with widespread consumer applications (for example, adding a sensor to every object in a store). However, when sensor dimensions are limited to a few millimeters, useful lifetime is limited by the capacity of miniature batteries. Often, it is not practical or cost effective to replace batteries or even physically access the sensor for recharging. Wireless power transfer is a convenient and robust way of powering/recharging sensors remotely but the acceptable distance between wireless power source and sensor needs to be increased for practical applications.



*Potential applications of “pad-less” wirelessly powered transmitters and receivers include addition of miniature sensors to everyday objects for usage analysis, monitoring and location. Image provided by Arun Natarajan, Oregon State University.*

In this CDADIC project, researchers sought to achieve longer wireless powering range for ultra-miniaturized mm-scale sensors. Such tiny sensors can be potentially low-cost. Their small size, however, limits application of traditional wireless powering optimization techniques. Researchers achieved improved performance by developing a systematic circuit design algorithm that optimizes wireless powering for a given sensor area and/or frequency of operation. They also recently demonstrated how this breakthrough’s novel circuitry improves energy harvester performance when starting from zero stored energy. In all cases, the focus has been on integrated technologies that have proven track records of low-cost manufacturing. Such developments have enabled the digital revolution of the past decades.

Other researchers have also been looking at this challenge - prior work on ultra-miniaturized mm-scale sensor transmitters and receivers have shown “pad-less” operation, i.e., the transmitter, receiver, and energy harvesting circuits are all fabricated in a single, inexpensive, integrated circuit that does not require any subsequent packaging or other components.

## Center for the Design of Analog-Digital Integrated Circuits (CDADIC)

This breakthrough approach extends the range of such “pad-less” integrated sensor wireless transmitters and receivers by increasing the range of wireless powering. The work also includes a new way of fabricating a miniature antenna along with the transmitter and receiver on the integrated circuit (IC). The new wireless approach ensures more power from the transmitter is radiated by the antenna compared to current state-of-the-art, which means that less energy is required from the battery to wirelessly send a given amount of information.



*Miniaturized low-cost wirelessly-powered sensor tags can transform asset and people tracking applications.  
Credit: iStock*

The wirelessly-powered sensors targeted in this research can significantly impact tracking objects of interest - they can be used for asset-tracking for miniature objects (for example, individual units in a store) or people tracking (for example, in elder-monitoring in assisted-living facilities).

**Economic impact:** The IoE represents the next stage in the evolution of society towards real-time data analysis and optimized control. The ways in which everyday technologies and tasks can be impacted by the IoE is only limited by individuals’ imagination. This will translate to new technologies that improve productivity and health in society. Miniaturizing such sensors and making them inexpensive enables both replacement of sensors in current applications as well as open new applications. Therefore, such sensors will form a significant enabler for the >\$1T IoE economy. CDADIC researchers are working with Texas Instruments and Intel towards the next generation of such sensors to enable commercialization. Finally, on-going research is preparing graduate students for careers in industry and research, creating engineers who will drive future innovations.

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# Center for Dielectrics and Piezoelectrics (CDP)

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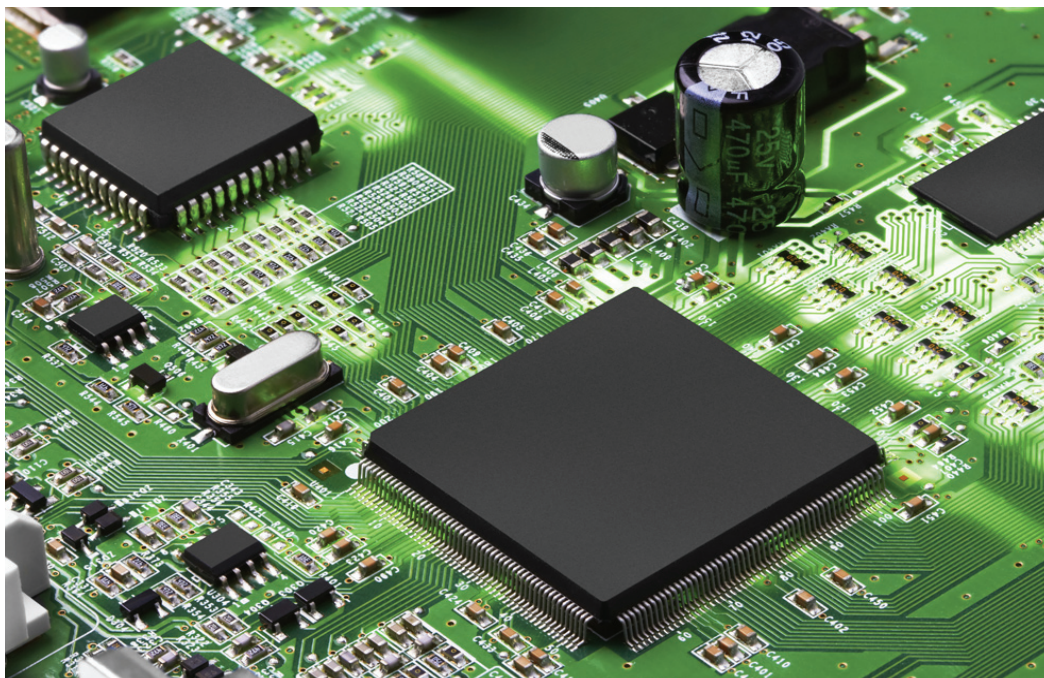
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## Improving the Reliability and Lifetime of Ceramic Capacitors

Ceramic capacitors serve as critical energy storage and management devices in consumer electronics; a multi-billion dollar industry. Research at the Center for Dielectric and Piezoelectrics (CDP) has lead to improved understandings of the mechanisms that control the reliability and lifetime of multilayer ceramic capacitors (MLCC) under electric fields.

New characterization methods have been developed to study dielectric degradation in highly accelerated lifetime testing conditions. The work has provided insights into the electrochemical processes responsible for degradation and breakdown. These breakthroughs have enabled the development and deployment of modified materials and processes to enhance the reliability of base metal electrode (BME) MLCC. In addition, the work has lead to new quality assurance methods that can identify capacitors predisposed to premature failure.



*An example of an electronic circuit board. Credit: iStock*

## Center for Dielectrics and Piezoelectrics (CDP)

Accelerated testing of multilayer ceramic capacitors at temperatures and voltages that exceed their rated values has long been used to estimate component lifetime under actual operating conditions. Until recently, a relatively simple model provided acceptable correlations between accelerated and normal operating conditions. But in recent years, to increase the energy storage capabilities and device miniaturization, dielectric layer thicknesses have been reduced, the number of dielectric layers has increased, and operating voltages have been reduced. In addition, nickel electrodes have replaced costly precious-metal electrodes. As a result, the effectiveness of the previous model substantially declined.

The CDP research team has developed more complete and accurate understandings of the underlying degradation mechanisms. The breakthrough has led to more accurate predictions of capacitor lifetime in typical device operating conditions. The work has also enabled dramatic improvements in the lifetime and reliability of MLCCs through refinement of both material composition and processing conditions.

End-user product/processes affected: The CDP work has primarily impacted the ceramic capacitor industry, but may also benefit other types of capacitors (such as tantalum or aluminum electrolytic capacitors) and other electronic ceramic devices such as actuators, sensors and micro-electro-mechanical (MEMs) devices.

The aforementioned work has further enabled the ongoing increases in capacitive volumetric efficiency of base metal electrode multilayer ceramic capacitors; thus enabling more capacitance per unit volume for continued capacitor miniaturization without sacrificing reliability. This makes possible smaller, thinner, lighter and more powerful electronic devices (cell phones, tablets, cameras, etc.) The work has also extended the useful temperature and voltage operating ranges of BME MLCCs. This allows them to perform in increasingly demanding applications such as on-engine-control, down-hole drilling of oil/gas wells, as well as military and aerospace applications.

**Economic impact:** Global sales of MLCCs is estimated to be \$10 billion annually. It can safely be assumed the impact of this breakthrough will exceed millions of dollars per year in sales. It is more difficult to estimate how the related improvements in MLCC performance will impact the performance and sale of the billions of electronic devices in which MLCC are essential components.

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# Center for Electromagnetic Compatibility (CEMC)

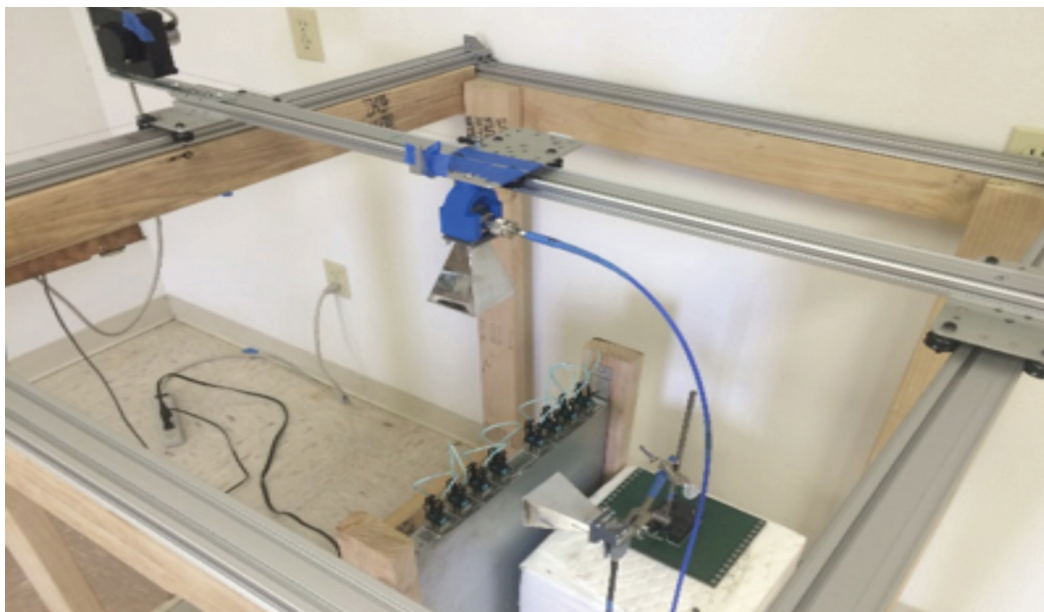
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## Sparse Emission Source Microscopy (ESM) Scanner with Super-Resolution Capabilities

Localization and identification of electromagnetic interference (EMI) sources is a major problem of electromagnetic compatibility (EMC). High-speed electronic devices produce Emission Source Microscopy (EMI) in a wide frequency range. This is due to multiple radiation coupling paths that involve structures such as cables, heat sinks, connectors, enclosure slots, ventilation openings, etc. Traditional EMI source localization techniques such as near-field scanning often produce ambiguous results that do not adequately identify and quantify the sources and coupling paths.

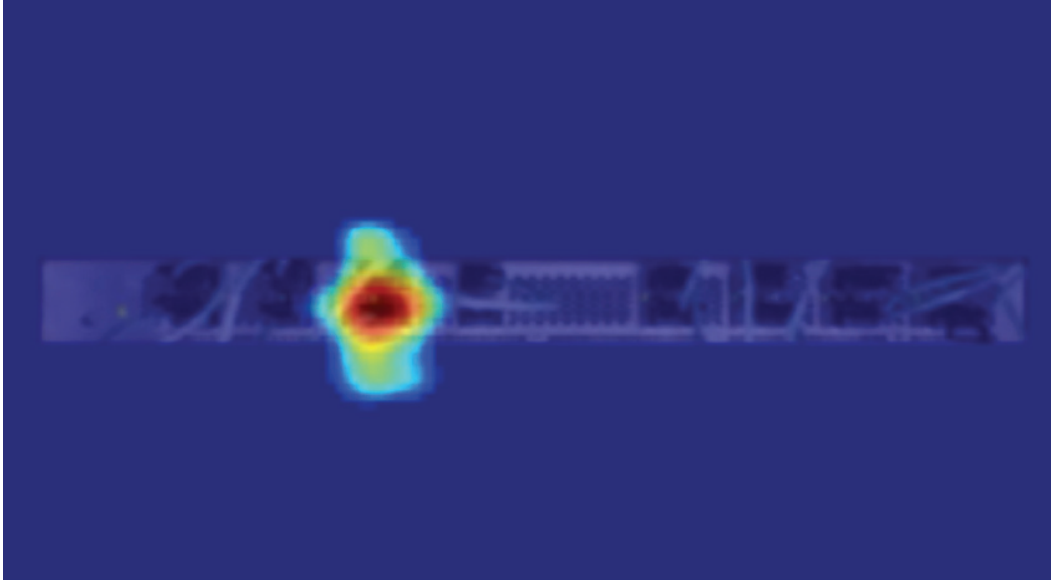


*Set-up of an emission source microscopy (ESM) scanning a device under test (DUT). Image provided by Victor Khilkevich, Missouri University of Science and Technology.*

This breakthrough's sparse emission source microscopy scanning provides a method for quick and robust localization of the EMI sources along with an estimate of the radiated power of each source. The measurements are performed by recording the field magnitude and phase on the plane above the device under test (DUT) as shown in Fig. 1, and by applying a focusing algorithm to obtain the microwave image of the radiating sources as shown in Fig. 2. A probing antenna is located at a distance of several wavelengths from the DUT. This makes for optimal receiving antennas. Manual scanning, together with the real-time imaging,

## Center for Electromagnetic Compatibility (CEMC)

allows adaptation of the scanning strategy to the particular type of the DUT. It only scans in areas relevant to an EMI coupling path under scrutiny. This dramatically decreases scanning time; from hours in traditional scanning methodologies to minutes in the current approach.



*Image of the radiated sources at 10.3125 GHz using the ESM scanner. Image provided by Victor Khilkevich, Missouri University of Science and Technology.*

To improve the resolution of the scanner, a water immersion technique is used. This is analogous to liquid immersion in optical microscopy. In water immersion scanning, a plastic tank is placed underneath the scanner frame and filled with water such that the probing antenna is completely immersed. The DUT is placed underneath the tank to avoid contact of the liquid with the electronics. Due to the high permittivity of water in the lower GHz frequency range (around 90 at 1 GHz), and, hence, a short wavelength, resolution is significantly improved; reaching 2.5 cm at 1 GHz. This is a 6-fold improvement over scan in air, allowing resolution of individual components on typical printed circuit boards.

**Economic impact:** There is a growing market for EMC field scanners; however, most of the scanners on the market are expensive robotic models with prices starting from tens of thousands of dollars. The sparse ESM scanner developed by the CEMC provides an inexpensive alternative with a cost under \$2000, not including the vector network analyzer receiver. The ability to generate EMI source and coupling path images within several minutes makes the scanners a unique tool allowing EMC engineers to more timely locate EMI sources with higher accuracy and confidence at the prototyping stage. This lowers the risk of EMI compliance problems late in design cycles. It can be applied to diagnostics for quick fixes of existing problems. Estimating the radiated power of identified sources with ESM avoids time-consuming trial-and-error in anechoic chambers to achieve compliance. Application of the sparse ESM scanner in the EMC design process can signif-

icantly reduce engineering time and the costly EMI retrofits required to achieve EMI regulatory compliance.

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## Fixture De-embedding for High-Speed Interconnect Characterization

Modern computer systems use high speed differential serial links as input/output (I/O) interfaces, such as USB, PCI-Express, SATA, etc. The data rate of differential serial links has grown exponentially over the last two decades to meet ever-increasing bandwidth requirements. When USB1.1 was introduced at 1998, it was running at 12 Mbps. Fast-forward to today, USB3.1 is running at 10 Gb/s, almost 1000 times faster than USB1.1. With increasingly fast data rates, signals propagating in the printed circuit board (PCB) degrade significantly due to the non-ideal effects such as copper surface roughness, the fiber-weave effect, dielectric dispersion, noise interference, etc. In other words, the signal propagation path in the PCB needs to be characterized and designed properly, otherwise high speed signals cannot propagate with enough fidelity and errors can then occur.

Measuring PCB structures is challenging, especially at high frequencies. The main reason is that test fixtures are necessary to connect the PCB structure under measurement to the measurement instrument. At high frequencies, the effects of the test fixtures become significant enough so that the measured results do not reflect the actual behaviors of the PCB structure. To remove the effects of the test fixtures, some methodologies such as TRL (thru-reflect-line) and LRM (line-reflect-match) were developed. These error-correction methods require several calibration patterns with different loadings. The calibration patterns need to be constructed in the same PCB as the PCB structure under measurement, which occupy a large amount of board area. The resulting error correction procedure can be cumbersome, involving several additional measurements. It demands uniformity among the calibration patterns that are difficult to achieve due to manufacturing variations.

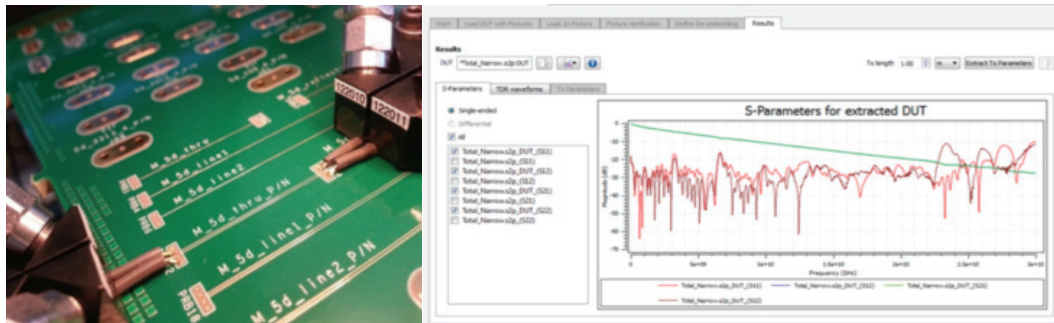
To address the challenge, CEMC researchers developed a new type of de-embedding methodology. The breakthrough de-embedding approach uses only one 2X-Thru pattern, as compared to six patterns needed for the TRL calibration to cover the frequencies up to 50 GHz. In this new approach, the S-parameters of the 2X-thru structure are measured first. Assuming the 2X-Thru structure is approximately symmetric, the S-parameters of a 1X structure can be calculated directly from the 2X-Thru measurement. Once the S-parameters of the 1X structure on both sides on the DUT are obtained, the S-parameters of the DUT can be readily calculated. This significantly simplifies calibration/de-embedding procedures as compared to the traditional TRL calibration where six calibration structures are typically needed. An engineering tool has been further developed to help the industry address this design challenge.

This work represents a significant improvement over the previous state of the art because the new methodology tool: 1) fits well with "real-world" engineering practice and does not require that users understand the electromagnetics, algorithms and mathematics; 2) significantly simplifies the calibration pattern designs and measurement procedures, and reduces measurement time; and, 3) are flexible enough and sufficiently effective to handle the complex real-world structures that are necessary to characterize high-



## Center for Electromagnetic Compatibility (CEMC)

speed interconnects. Combined with different probe designs, they can be used for applications ranging from laboratory measurements to product-line testing.



*(Left) A differential printed circuit board trace is measured using micro-probing station. To characterize the electrical performance of the trace only, the effects of the probes and the probe pads need to be eliminated from the measured results. (Right) A screenshot of the developed engineering tool. Images provided by CEMC.*

Another significant contribution from Center for Electromagnetic Compatibility (CEMC) is de-embedding sensitivity analysis. De-embedding practices among current industry tools are following a brute-force approach, wherein results are generated by the tool without error checking. In-depth de-embedding analysis are then performed by the CEMC research team to reveal the mathematical relationships between de-embedding errors versus the quality of fixture designs. This breakthrough helps users to understand how good the de-embedded results are and significantly reduces the possibility of unknowingly using data beyond valid frequencies.

**Economic impact:** The developed engineering tool has been used in several CEMC member companies including Intel, Cisco, and IBM. The cost reduction alone generated by using the tool instead of alternative commercial software is estimated to be at least \$100K a year among these companies. Further, the innovative methodology significantly reduces costs of fabricating complex calibration patterns. It significantly shortens the measurement time from a couple hours for one DUT to less than 30 minutes and is much less prone to error. The associated cost savings are estimated to be at least \$2M/year at this stage for these companies. The tool can also be extend to other interconnects beyond PCB (such as connector, cabling, etc.), which can further increase the economic impacts.

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# Center for Tire Research (CenTiRe)

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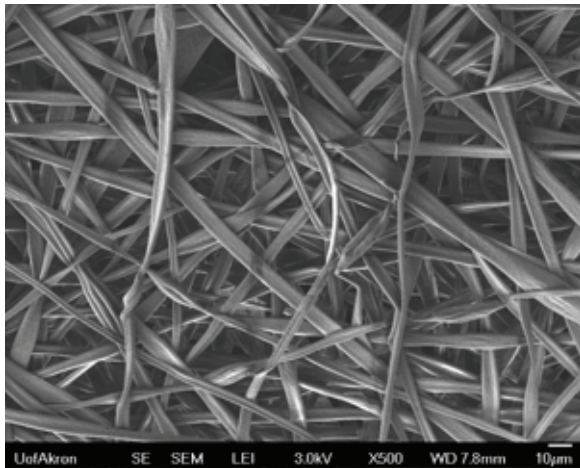
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## Recyclable Thermoplastic Rubber: A Boon for Tires and Healthcare

This project addresses important technology gap(s) as it translates from research discovery toward commercial application. It enables production of halogen-free rubber on a commercial scale. The breakthrough product will compete with current halobutyl rubber (current global production is ~1 million tons per year) by producing thermoplastic biocompatible rubber that requires fewer resources to produce and a simplified production process. This breakthrough material is much easier and cheaper to make than earlier versions of polyisobutylene-based thermoplastic rubbers. As a result, that scale-up is faster; the reactions are usually complete in less than 10 minutes.

In radial car tires there is a thin layer of halogenated butyl rubber to keep the tire inflated -- without that drivers would have to pump up their tires almost daily. The original aim of this research was to produce butyl-type polymers by copolymerizing isobutylene with alloocimene, a terpene from natural resources, using the commercial butyl rubber process.



*Scanning Electron Microscopic image of the drug eluting fibers.  
Image provided by Judit E. Puskas.*

Alloocimene is a renewable monomer. Allomatrix can also be crosslinked if necessary. Initial tests indicate that it is quite biodegradable under specific conditions. This is the first material that could be a potential replacement of halobutyl rubber without halogen content. It can be electrospun into a drug eluting fiber mat to be used on medical implants.

## Center for Tire Research (CenTiRe)

With additional support from the Rubber Division of the American Chemical Society, Wyatt Technology and the Breast Cancer Innovation Foundation of Akron, supporting the research of integrating breast reconstruction with cancer diagnosis and treatment using electrospun Allomatrix fiber mats. Puskas received a PFI:AIR Research Alliance Grant from NSF, with maximum matching (\$800,000 from NSF matching > \$800,000 cash from industry and investors). The PFI:AIR project focuses on the translation and transfer of the Allomatrix technology and the development of an academic-based innovation ecosystem.

The new breakthrough copolymers (referred to as "Allomatrix") are thermoplastic rubbers that can be more easily melted and recycled. They have a high potential for replacing halobutyl rubber in car tires and for health care applications such as pharmaceutical stoppers and implant coatings. An earlier thermoplastic rubber that contains isobutylene and styrene, co-invented by a University of Akron researcher, is used as a drug eluting coating on Taxus coronary stents. Such stents have been implanted into more than 6 million patients since its FDA approval in 2004, saving countless lives. Based on the development of the stent coating rubber and Allomatrix, the "Rubber World" journal listed Puskas among the 125 inventors who had major impact on the rubber industry during the past 125 years.



*Car tires could be made from a more biocompatible rubber that requires fewer resources to produce and a simplified production process. Image courtesy of Goodyear.*

The Allomatrix family of polymers uses raw materials from renewable resources, and is a potential replacement of halobutyl rubber, which is used to make the gas-barrier inner liner of car tires and pharmaceutical stoppers. It also has the potential to be used as a rubbery biomaterial that can be processed as plastic and can be recycled, with better combination of properties than silicone rubber. These features provide the performance of commercial halobutyl rubber without the presence of harmful halogens. With further development, this project has the potential to bring back high value-added manufacturing to the USA, especially for biomedical applications, creating jobs in the STEM disciplines.

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# Center for Electrochemical Processes and Technology (CEProTECH)

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## Advanced Water Treatment for Hydraulic Fracking Water

One of the energy sources widely available in the United States is natural gas. According to the U.S. Energy Information Administration (EIA), between 2005 and 2013 the total natural gas production in the U.S. has increased by 35%. This has been due largely to developments in production of natural gas from shale formations. In the last decade, the use of hydraulic fracturing or fracking process to extract natural gas from shale formations has skyrocketed.



*The laboratory set-up of individual components used in the Advanced Water Treatment skid. The hydrodynamic cavitation unit is at the forefront, the UV-ozone generator is mounted on the wall, and two storage containers for testing the real produced water. The electrochemical cell along with hydrodynamic cavitation unit and UV-ozone generator form the Advanced Water Treatment skid. Image provided by Madhivanan Muthuvel, Center for Electrochemical Engineering Research, Ohio University.*

Hydraulic fracturing (HF) is a development process of injecting water, containing sand and chemicals, in wells under extremely high pressure to fracture or crack open pores in the shale formation to release the oil and gas. Hydraulic fracturing process injects large quantity of water (~ 100 million gallons) per well. Ground water and surface water resources are withdrawn to account for the large volume of water needed for the hydraulic fracturing process, which directly influences the availability of ground and surface water for other consumptions. The flow-back water and produced water obtained during the hydraulic fracturing process contains organic chemicals, dissolved metal ions, total dissolved solids, and chemical additives. If the flow-back and produced waters are not sufficiently treated and discharged to bodies of water, then contamination of ground and surface water could have serious health issues to humans and animals. Therefore, water management and wastewater treatment presents major technical and economical challenge to the hydraulic fracturing technology.

The focus of this breakthrough work is to combine different methods such as, mechanical, photochemical, and electrochemical, to treat the wastewater generated by the oil and gas industry, especially that produced water from hydraulic fracturing process. A skid was developed by De Nora Tech, by combining three technologies - hydrodynamic cavitation system (mechanical), UV-ozone generator (photochemical), and electrochemical cell (electrochemical oxidation) to treat flow-back of fracking water. The skid unit was designed to treat 5 gallons of wastewater per minute (gpm) with capability to scale up to 400 gpm. The objectives for this investigation was to: evaluate the functioning of the skid in treating the real produced water from hydraulic fracturing process; abate the primary constituents of the produced water to meet the National Primary Drinking Water Regulations, and; provide recommendations to improve and optimize the skid.

The skid was subjected to real produced water from a gas well to evaluate treatment efficiency for its primary constituents. The produced water had volatile organic compounds including benzene, toluene, ethylbenzene, and xylene commonly referred as BTEX, nitrogen-containing compounds, and dissolved metal ions such as iron and manganese. The key findings are that the combination of three technologies has completely broken down the volatile organic compounds (BTEX) found in the produced water, the concentration of iron was reduced by 83.3%, the manganese concentration was lowered by 87.5%. The concentration of nitrogen-containing compounds expressed in terms of total kjeldhal nitrogen (TKN) was reduced by 95%. The concentrations of BTEX, nitrogen-containing compounds (TKN), and manganese in the treated water was compliant with the National Primary Drinking Water Regulations.

Conventional methods of treating wastewater containing volatile organic compounds involves the use of expensive UV-ozone irradiation method. In the case of dissolved metal ions, chemicals are added to the wastewater resulting in formation of precipitates, which needs further treatment.

The advantage that this breakthrough Advance Water Treatment Unit has over the conventional methods is portability, economical, and ease of operation for this robust system. The Advanced Water Treatment Unit completely removed the volatile organic compounds, especially BTEX (known carcinogens).

The Advanced Water Treatment Unit is a simple and effective way of combining three proven technologies (hydrodynamic cavitation, UV-ozone, and electrochemical cell) for treatment of produced water to meet the National Primary Drinking Water Regulations. For the oil and gas industry, better treatment of wastewater should increase its reuse and reduce the demand for fresh water for the hydraulic fracturing process. It is projected that an average of 2.4 billion gallons of produced water are extracted every day. This Advanced Water Treatment skid is portable. It can operate on-site and can handle 400 gpm of wastewater. The treated water at least has the potential to be reused for the hydraulic fracturing process.

**Economic impact:** The three technologies included in the Advanced Water Treatment skid was arranged in a Plug-n-Play model, meaning multiple units of these technologies can be added or removed depending on the water quality of produced water and treated water. The largest waste stream in oil and gas production is the produced water with an average of 2.4 billion gallons extracted per day. In the hydraulic fracking process, the cost for transportation, includes bring water on-site for well development and transferring produced water for treatment or disposal, is estimated at \$0.50 to \$8 per barrel. The mobility and small footprint of Advanced Water Treatment Skids should make it easier to treat produced water on-site thereby saving some of the transportation costs. Current estimated cost for treating the produced water varies from \$0.20 to \$8.50 per barrel based on the technology, location (on-site or off-site), and end use. The ability to remove key constituents (BTEX, manganese) from produced water to meet the Water Regulations using the current configuration of the Advanced Water Treatment is a strong indicator for efficient treatment technology. One of the goals of this research it to bring the cost for treating the produced water between \$2 and \$4 per barrel using the Advanced Water Treatment Skid.

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# Center for Embedded Systems (CES)

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## Distributed Run-Time Management for a Multi-Agent System

In today's automotive environments, embedded electronic control units (ECU) are customized, each handling pre-specified inputs and services. However, multiple ECUs with different non-transferable functions result in highly failure-susceptible systems. This unpredictability is aggravated by the scalability of the interconnected components, by the increased complexity of their interactions, and by the potentially serious risks consequences posed by the unpredictability. Software errors, aging, security, legacy software, and increased performance requirements add to the complexity required for maintaining reliable real-time car systems. Taking into account all the aforementioned characteristics and the specific automotive requirements and standards, distributed resource management becomes the most promising solution to these problems.



*The proposed on-vehicle multi-agent system can offer smarter and more secure communications between vehicles' numerous electronic control units, thus making possible improved distributed error recovery, safety, and functionality transfer. Image provided by Iraklis Anagnostopoulos, SIU.*



## Center for Embedded Systems (CES)

Consumer surveys indicate that more than a quarter of car buyers consider Internet connectivity more important than other key auto features such as engine power and economy. Because it will generate huge quantities of data, this new interconnectivity will interact with and impact the entire world in many ways. As smart cars continue to evolve new applications and services will build upon communications between cars, smart buildings, news and alert services, weather and security interests, and smart cities. From navigation services to "mobile" office environments, modern smart-car systems need to be capable of automatically and dynamically integrating and supporting almost all user-end devices. Thus, distributed run-time management and distributed ECUs will prevail as the key multiple integrated technology to efficiently and effectively address all the aforementioned issues.

Integrated multi-agent software components are no longer bound or confined to specific hardware. They can now be executed on various embedded units in support of all types of run-time service migrations. Each embedded ECU can act as run-time replacements for other ECUs, thus resulting in lower susceptibilities to failure.

In this project, CES researchers at Southern Illinois University coupled multi-agent systems with run-time resource management to develop a distributed framework for run-time management of multi-agent systems. The framework is based on the idea of distributed co-operative agents. These provide self-management functions while maintaining system requirements. Some of the framework's distributed functionalities include dynamic resource mapping task and management, error management, node discovery and service migration.

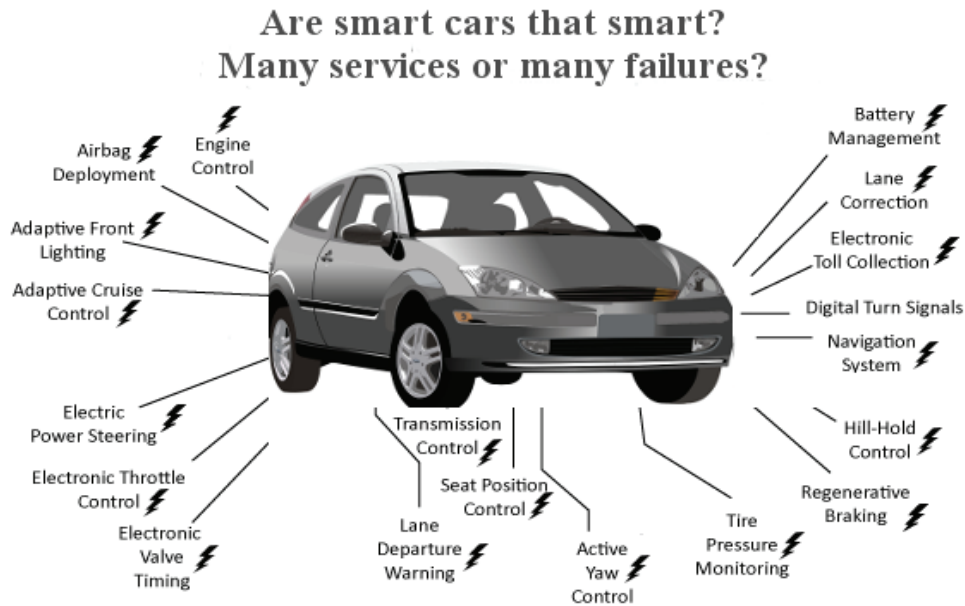
This work brings extended innovation to the field of "smart" cars by combining state-of-art technologies and integrating distributed run-time services for multi-agent systems. The resulting services offer improved real-time support, more powerful fault tolerance and intelligent decision making along with improved overall system monitoring.

Previous methodologies have suffered from central points of failure. They typically have had limited scalability; meaning that decisions could not be easily made at run-time. This CES/SIU/C breakthrough combines reactive and co-operative communication schemes. Resulting systems are therefore capable of making more reliable decisions and predictions by employing improved methods for self-management.

This work complies with a consideration number of automotive industry and standards. Automobile navigation, car security, infotainment requirements, travel information, cruise control etc. are a few of many examples of services that are highly depended on ECUs. This breakthrough's framework offers unprecedented integrated diagnostic opportunities because it deploys targeted diagnostic agents to deep-dive potential error states within automobiles. The distributed approach also offers improved uptime and reliability through the redeployment of tasks to available nodes for processing. Moreover, it enables leaner on-board microcontroller platforms by triggering executable agents when needed, as opposed to executing them continuously in the background.

This work and its improvements and new solutions for self-management, will result in better control and security. Cars will become more capable of adapting to the driver. Principles and techniques employed in this breakthrough may be adapted and integrated with other systems that require distributed control and communication.

**Economic impact:** Automobiles are well on their way to becoming the most sophisticated of all connected devices. The smart car market is expected to be worth \$274 billion by 2017. Across the world, roughly 23 million cars on the road today are connected to the Internet, and that number is expected to soon increase to over 150 million. The number of connected cars may soon exceed a quarter of a billion worldwide. Projections indicate that by the year 2020, 16 billion dynamic-networked devices will be deployed.



*Smart cars contain multiple embedded electronic control units. The concern is that multiple ECUs that have different non-transferable functions result in highly failure-susceptible systems. Image provided by Iraklis Anagnostopoulos, SIU.*

This breakthrough's automatic node discovery functionality will allow vehicles to more easily adapt to new technologies and communication protocols with the outside world. The constraints of the harsh and demanding environment inside vehicles and real-time application requirements are more easily integrated and taken into consideration by the proposed framework. Instead of having continuous monitoring, resource management is achieved more efficiently than was possible with previous state-of-art methodologies. Because the multi-agent system will more seamlessly integrate new features, it will be more feasible to launch and download smart car monitoring services with minimal modifications in software and hardware architectures.

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## Hybrid Multicore Productivity Research (CHMPR)

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### Quantum Learning - Machine Learning using D-Wave's Quantum Computer

In support of D-Wave Systems, a CHMPR member, and sponsored by a NASA grant to explore the potential viability of the D-Wave quantum annealing computer which is to be a future disruptive technology, CHMPR staff scientists implemented the largest known working Neural Net multi-hidden layer algorithm (called a Boltzmann Machine in the literature). The D-Wave 2X system is owned by Google and shared with NASA Ames.



*D-Wave 1,000 qubit processor. Image provided by D-Wave Systems, Inc.*

## Hybrid Multicore Productivity Research (CHMPR)

To design and test a Neural Net, many in the industry use MNIST, a well-known and freely available set of handwritten images of digits. In this breakthrough approach to machine learning, the computer program undergoes "supervised learning" wherein a "training set" is used to acquaint the computer program with what numbers look like. The program is "trained", and then a "test set" is used to see how well the computer program does.

While the set of all possible 28x28 MNIST images is an impossibly large set for a classical computer to explore, the D-Wave2X is able to explore such a vastly large set very quickly. The D-Wave2X is programmed using a set of biases and weights. The researchers set up an initial set of biases and weights, and then in subsequent runs of the computer program adjusts them to get closer and closer to representing the training digits with the model comprised of the biases and weights.

However, "single layer" machine learning computer programs that have one set of biases and weights, are not able to do well representing digits, because the representational power of a single set of biases and weights is small. Researchers then introduce multiple layers of biases and weights to model more complex relationships between different pixels (or the input data, or the labels). These layers are known as "hidden layers" in Boltzmann machines.

It may seem as though it is always a good idea to increase the representational power of a model. The drawback, however, is that the more parameters a model has, the harder it is to train the computer. The main thing is to have a model that has enough freedom to be able to represent the data. For natural data, having as many parameters as computationally possible seems to be the best approach (hence the success of deep learning which have many layers of nodes).

The UMBC research team first used a single layer on the D-Wave System, achieving 99% recognition of the digits trained on. Approximately 70% recognition was attained on digits not trained on. Then, two hidden layers were used, using a hybrid model with both the D-Wave system and a classical system. This approach enabled researchers to use connections both within and between the layers. Finally, a three-layer neural net was started using the D-Wave System for the hidden layers.

With advancements in computational systems environments promising exascale performance in the near future, the ability to solve large, multifarious scientific problems in various science and engineering fields has increased. The quantum hardware finds solutions to quadratic binary optimization problems (QUBOs), by drawing samples from a probability distribution. Using adiabatic quantum annealing with over one thousand qubits on the D-Wave 2X, UMBC researchers are using this breakthrough technology to construct powerful machine learning algorithms based on probabilistic frameworks.

Further, UMBC's implementation approach - using the D-Wave 2X with a classical computer in a hybrid manner - enables researchers to encode thousands of neurons, employing all the qubits for each of the hidden layers in the neural net. This construct expands the size of the problem set that can be solved with the current D-Wave quantum processor, enabling researchers to do Quantum Computing for large problems with real-world relevance.

In an interesting application, working with NASA researchers, UMBC will apply this neural net to remotely sensed CO<sub>2</sub> data from the NASA satellite OCO-2. This should allow them to improve upon the inability of current hydrological model predictions to more accurately predict the fraction of annual global carbon

uptake by surface vegetation of the anthropomorphic CO<sub>2</sub> atmospheric loading; which current estimate put at ~20%.

UMBC anticipates applications in further learning systems, including applications to improve software for binary classification, multi-label classification, image segmentation, and sparse image processing, leading to improved computer vision, natural language processing, and robot control. The end-user products and services that this enables are endless.

**Economic impact:** Improving time to insight using D-Wave quantum computing systems for deep learning will lead to other scientific breakthroughs. It will also increase revenue opportunities through new innovative products and services. It will also result in cost savings opportunities for commercial companies across industries.

The bottom line is that any application that is improved with advanced pattern recognition and predictive modeling, will benefit from this breakthrough. Personalized medicine, cancer drug discovery, and financial predictions are but a few areas with significant potentials to benefit society in major ways.

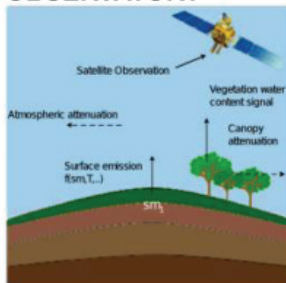
## Calculating Annual Carbon Uptake from OCO-2 and Photosynthetic Modeling using D-Wave

### ORBITING CARBON

### LAND SURFACE MODEL

### D-Wave Quantum Annealing

#### OBSERVATORY



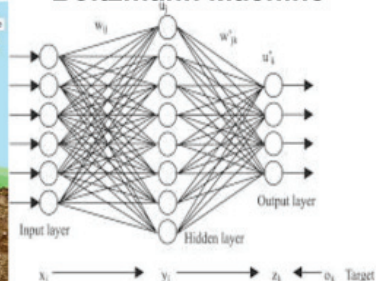
Measures surface CO<sub>2</sub> from space

#### CARBON UPTAKE



Vegetation model needs  
Fluxes from Station Data

#### Boltzmann Machine



NN trains CO<sub>2</sub> to infer  
CO<sub>2</sub> fluxes CO<sub>2</sub>

*Calculating Carbon Uptake from OCO-2 and Photosynthetic Modeling Using D-Wave. Image provided by D-Wave Systems, Inc.*





# Center for Health Organization Transformation (CHOT)

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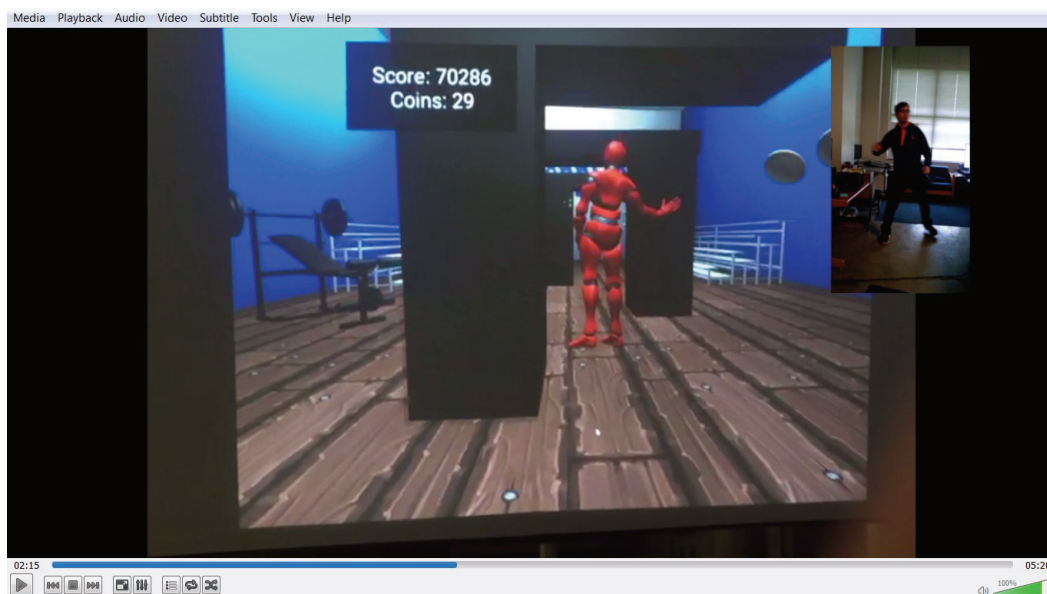
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## Achieving Enhanced Patient Wellness Outcomes through Gamification

The term "gamification" is an emerging paradigm that aims to employ game mechanics and game thinking to alter behavior and improve desirable outcomes by promoting better patient compliance. The objective of innovative project was to investigate the fundamental aspects of gaming (both traditional hardcore gaming and casual mobile gaming) that make them engaging, rewarding and stimulating and to apply those to immersive, and fun, healthcare wellness management solutions that can be adopted by patients.



*An individual performing physical activities by following the challenges presented in the virtual gamified environment. Image provided by Conrad Tucker, Engineering Design and Industrial Engineering, Penn State University.*

The current physician-patient relationship is most often top-down in nature; a physician provides a patient with a specific set of instructions with which they are supposed to comply. The patient is then to go home to manage their care until the next provider/hospital visit. In the context of healthcare, gamification aims to transform the patient-physician relationship into a more collaborative experience, where patients become

## Center for Health Organization Transformation (CHOT)

more motivated to succeed in their care and wellness management goals because of appealing features designed to keep them engaged.

This work addresses the question of whether patients exposed to "wellness gamification" have better health outcomes, compared to patients that are not. The scientific contributions of this work have the potential to transform the manner in which patients are motivated to adhere to medication regimens, physical guidelines, and other wellness initiatives by incorporating the features of games that make them engaging, motivating and social in nature.

It is relatively well established that individuals who are prone to use similar self-improvement platforms are already committed to the success of their wellness management. This complicates work in this area. The main limitations of existing self and wellness care techniques are that too many patients do not engage with such systems for a prolonged period of time.

This research has resulted in the creation of: 1) a theoretical framework that outlines the factors needed for a successful gamification wellness solution; 2) a gaming system platform that explores the practicality of the proposed theoretical framework in influencing patient behavior, towards better wellness outcomes, and; 3) new knowledge about the extent to which patients attain better wellness outcomes when exposed to a gamification-based wellness management system.

In addition to patients, the concept of gamification has the potential to transform healthcare officials by creating incentive structures that encourage them to be more efficient, productive and engaged in the overall process of patient-centered care.

**Economic impact:** Unlike the current healthcare paradigm, a more gamified healthcare system has the potential to enable patients to transform from passive consumers of health-related content, to proactive agents who are motivated to play a conscious role in their overall wellness. This breakthrough gamification work has the potential to transform medication adherence and compliance from a task into an activity in which patients are more motivated to partake.

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## Perioperative Surgical Home (PSH) Study

This work of researchers at Texas A&M's Center for Healthcare Organization Transformation (CHOT) is a first-of-its-kind, large-scale national survey and systematic literature review focusing exclusively on perioperative safety and quality. The resulting Perioperative Surgical Home (PSH) Model is a physician-led care delivery model that includes multi-specialty care teams and cost-efficient use of resources. Simply put, PHS is a patient-centered continuity of care delivery model that incorporates shared decision-making. The two-year study focused on how the PSH reduces surgical care costs while improving clinical outcomes. It included: 1) a systematic literature review of PSH activities focused on clinical outcomes and cost savings; 2) an in-depth survey of 15 leading PSH programs in the U.S. designed to identify and better understand key PSH activities, and; 3) a gap analysis of residency training requirements for anesthesiology, internal medicine, surgery, and family medicine. The work has demonstrated that the model is capable of serving as a guide for future curriculum development.



*Researcher and trial participant. Credit: National Center for Complementary and Integrative Health, National Institutes of Health*

Results have demonstrated that successful evolution of the PSH requires the concomitant expansion of the perioperative clinicians' roles suggested by the PSH Model. Results have provided support for the CHOT sponsor ASA's framework and approach to alternative payment models by identifying the economic benefits of the PSH. They also suggest that anesthesiologists, hospitalists, surgeons, and nurses need to be actively involved in organization-wide strategy development and initiatives to improve care quality and reduce cost.

## Center for Health Organization Transformation (CHOT)

Subsequent follow-up studies by CHOT have identified gaps in medical education related to competencies for successful PSH development, helping to initiate conversations within ASA and with the American Board of Anesthesiology regarding medical education.

This breakthrough study has the potential for policy-relevant cost savings for policymakers, payers, administrators, clinicians, and patients across the perioperative continuum of care. This is due to the demonstrable substantial improvement its use provides in both safety and quality outcomes. This study also identifies specific areas of improvement for residency training programs that are necessary to address key PSH activities.

**Economic impact:** Surgical care is too often not standardized or coordinated. This can result in duplicated and/or unnecessary care that costs an estimated \$18 billion annually in the United States. Many Western countries have developed preoperative testing and assessment guidelines to improve surgical outcomes and the reduce costs of surgical care.

Based on results of this study, the PSH has potential for dramatic cost savings due to: 1) Better coordinated preoperative testing, potentially resulting in patient cost savings; 2) Improved rehabilitation programs; Improved preoperative patient education; 3) More effective operating room (OR) scheduling initiatives that have demonstrated 22.5% decreases in OR turnaround time; 4) More effective blood use programs that have the potential to save over \$100 per patient after implementation of group-and-save policies; 5) Improved nausea and vomiting protocols with 16% more patients achieving response standards with standardized protocol; 6) Improved early mobilization programs that demonstrated \$756/patient cost savings due to 1.8 day reductions in overall length of stay; 7) Better coordinated discharge planning initiatives that demonstrate \$412/patient reductions in total costs, and; 8) Overall, surgical cost savings estimated to be \$112 per surgical patient when using evidence-based pre-operative test ordering practice guidelines.

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## Outcome-Driven Treatment Delivery & Personalized Medicine

CHOT researchers focused on an evidence-based approach to treatment delivery. Two teams of investigators were involved: 1) a personalized treatment design team for diabetic patients, and; 2) an optimizing epidural analgesia procedures team.

The potential consequences of failed or misplaced epidural needles are well known to obstetric anesthesiologists. Inadvertent intravenous injection of local anesthetic into a vein in the epidural space can lead to seizures or fatal cardiac arrhythmias. Equally worrisome are inadequate epidural blocks leading to complications during caesarian sections.



*Applying an epidural to a patient. Credit: iStock*

This study sought to establish and quantify the safety and efficacy of a large-dose needle-based epidural technique in obstetric anesthesia. Through systems modeling and predictive analytics, a safe and quickly effective epidural dose is established that can then be administered through the epidural needle prior to the insertion of the epidural catheter.

## Center for Health Organization Transformation (CHOT)

The results indicate that a needle-based approach is 22% faster and more dose-effective (18% less drug) in achieving comparable sensory levels than the traditional catheter-based approach. The findings also suggest that injecting large doses (up to 20mL) in the epidural space through the epidural needle is generally safe and results in good outcome for the patients.

The end product of this work is a decision support system that can identify patients-at-risk of complications. It also highlights the best practice clinical practice guideline (CPG) that allows for standardized, safer, and more cost-effective epidural delivery with minimum complications.

The cumulative costs of approximately four million annual births are well over \$50 billion. This research demonstrates that it may be possible the use fewer drugs to achieve desired sensory responses with minimal hypotension. Reducing hypotension may also lead to safer process and possibly better long term outcomes. Providing quality of care with minimal complication is of paramount importance. Effective training of our new physicians (anesthesiologists) means more treatment success and improved efficiency. Given that physician time is expensive, this work thus reduces wastes in physician time and maximizes their productivity.

The management of gestational diabetes mellitus (GDM) requires close monitoring of patients' blood glucose levels while clinicians experiment with dosing based on a combination of clinical guidelines and their experience and judgment. However, conflicting guidelines and wide variation in practices can result in less than optimal care.

A challenge in diabetes management comes from the fact that different patients have different dose-responses and different disease progression characteristics. Hence, a personalized treatment plan tailored specifically to the patient's unique dose-effect characteristics may be more effective and efficient than current trial-and-error approaches.

In this project, CHOT researchers designed a novel outcome-based decision support tool that couples a predictive treatment-effect model with a planning optimization model. Specifically, a predictive model first uncovers treatment effects based on pharmacokinetic and pharmacodynamics (PK/PD) analysis of anti-diabetic drug dosages. Blood glucose levels are then recorded (self-monitored blood glucose) during the titration period of each patient. This information is then incorporated within a personalized planning model for optimal treatment. The decision support tool makes possible continuous learning for each patient as new treatment outcomes are recorded.

Tested on a group of 200 patients, using the first 2-3 weeks of treatment to establish the predictive drug effect, results indicate that the optimized treatment plan may offer improved glycemic control with lower drug usage compared with current practice.

The predictive PK/PD treatment-effect model becomes more precise as outcome data accumulate. Most PK/PD models require drug concentration levels in the blood but these are not generally measured. This new approach seems to overcome this obstacle while establishing more direct relationships between drug dosages and drug effects. Incorporating this information within a treatment planning optimization model allows clinicians to tailor outcomes and medication regimens to the individual patients' specific needs. Over time, this approach may lead to better treatment decisions and possibly improved outcomes.

In summary, the PK/PD treatment-effect model is a mechanism-based that captures each patient's underlying glucose dynamics and drug effects. By doing so it offers predictive estimates of dose glucose response

characteristics. It captures disease progression over wider treatment horizons. This helps assure that complying patients have the adequate glycemic control that is necessary for safe drug delivery. Because it uses only drug dosage and self-monitored blood glucose levels (SMBG) that are hopefully recorded accurately by patients at home, for compliant patients it is readily implementable with current clinical and patient practice. Last and most importantly, the model is tailored to each individual patient to obtain a personalized dose response and disease progression. This predictive information is then incorporated into a mathematical programming-based treatment model that optimizes their glycemic control and drug dosage.

The end product is a real-time clinical decision support system that enables clinicians to tailor treatment design to the needs of the patients. It should help clinicians make better treatment decisions.

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# NSF Center for High-Performance Reconfigurable Computing (CHREC)

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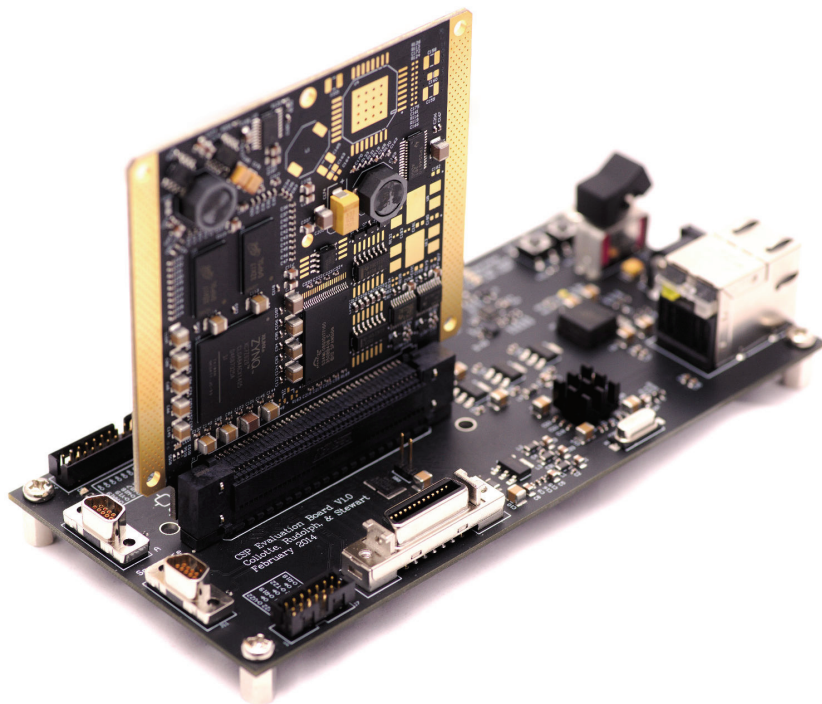
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## CHREC Space Processor (CSP)

For over a half century the U.S. space program has been a leading contributor to the health and growth of our nation from the perspectives of science, technology, economy, and defense. Given the nature and purpose of present and future spacecraft, be they for earth science, space science and exploration, or defense surveillance, one of their most daunting challenges is on-board computing. This challenge presents in two major areas: 1) processing of data from on-board sensors, and; 2) processing of data for autonomous-control functions such as docking, landing, and roving. In both areas, mission demands for space computers are rapidly increasing, while conventional on-board computing technologies are falling behind, in terms of the high performance required in harsh space environments with limited size, weight, and power, as well as the inherent hazards of radiation effects beyond our planet's atmosphere.



*CSP is a novel form of hybrid, reconfigurable space computer that can achieve an unprecedented mix of high performance and reliability with low power, size, weight, and cost. Image provided by CHREC.*

## NSF Center for High-Performance Reconfigurable Computing (CHREC)

In 2015, CHREC researchers achieved a major milestone in basic and applied research for spacecraft computing with the development and technology transfer to center members of the new CHREC Space Processor (CSP). The CHREC CSP is a novel form of hybrid, reconfigurable space computer that can achieve an unprecedented mix of high performance and reliability with low power, size, weight, and cost. As of December 2015, 14 new space missions (a technology pallet for the International Space Station, a space-science satellite, and 12 weather satellites) have adopted CSP. These have been scheduled for launch into Earth orbit in 2016 and 2017 for NASA and PlanetiQ (both are center members), equipped with a total of 39 CSP computers. Moreover, these and other CHREC members are evaluating CSP for additional missions.

The primary challenge with space electronics is how to prevent or at least mitigate the harmful effects of solar and cosmic radiation on electronics. Some devices feature radiation hardening in fabrication by process and design. This approach can usually minimize radiation effects on electronics; but not without trade-offs. Radiation hardening can result in lowered performance and larger sizes, weights, power consumption, and cost. These are due to the nature of the hardening process. Other devices, such as those used in consumer laptops, tablets, smart phones, etc., achieve high performance with lower sizes, weights, power consumption, and cost, but many of these technologies suffer from poor to no reliability when subjected to space radiation.

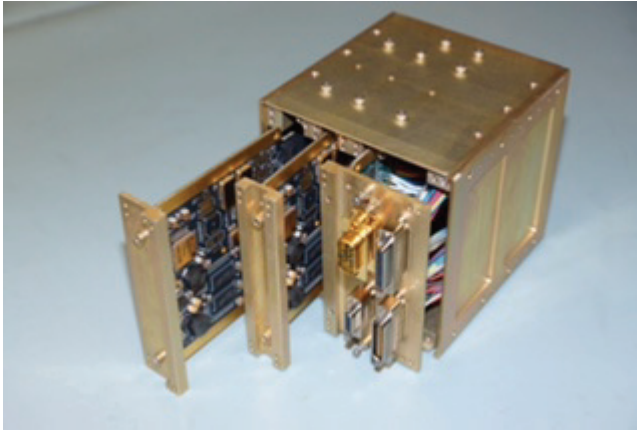
CSP features a novel, hybrid combination of higher-grade commercial devices (e.g., main processors and memory units) where performance is critical, and radiation-hardened parts (e.g., flash memory, watchdog controller, power and reset circuits) when reliability is critical. These can then be supplemented by a myriad of techniques (e.g., replicated bootstraps and configurations with RSA authentication, internal and external watchdog units, error-correcting memory units, and configuration memory scrubbing from the field of fault-tolerant computing. In this manner, CSP offers an innovative solution for space computing that is faster, lower size, lower weight, lower power, and less cost than fully hardened computers, while being more reliable than fully commercial computers.

CSP also features an innovative, reconfigurable, central processor, an FPGA SoC (i.e., field-programmable gate array, system on chip) known as the Xilinx Zynq. The Zynq in CSP contains a multicore CPU (twin ARM Cortex-A9 cores with Neon accelerators) able to execute (thanks to CHREC) flight software systems (e.g., core flight system or CFS from NASA Goddard) atop any one of several operating systems (e.g., Linux, RTEMS, Wind River's VxWorks). The Zynq also contains a potent, reconfigurable logic array that can be configured either on the ground or in flight to match the unique needs of each mission, application, instrument, etc., for faster speed and lower power.

**Economic impact:** The hybrid and reconfigurable approach of CSP is proving its potential to dramatically increase capabilities and reduce costs associated with spacecraft and space-based computing. The breakthrough could lead to significant economic impacts in the U.S. space industry. In terms of direct economic impact, instead of having to develop new, hardened processor technologies (at an estimated cost of \$20M+ for each new processor) and then exclusively rely upon these expensive (e.g., \$10K to \$100K per device) and slower devices for reliable space systems, the CSP approach enables future systems to more reliably achieve higher performance at lower cost and do so with less size, weight, and power. Moreover, with this approach, the space industry can rapidly exploit technology breakthroughs from the consumer marketplace as new devices emerge. The indirect economic impact here may even be more significant. New space missions may be made more feasible when this novel approach is used. Major savings may come from spacecraft and launch vehicles that are smaller and less expensive than would otherwise be the

case, resulting in scientific discoveries and economic benefits that otherwise might not have been realized.

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*Another view of CSP. Image provided by CHREC.*



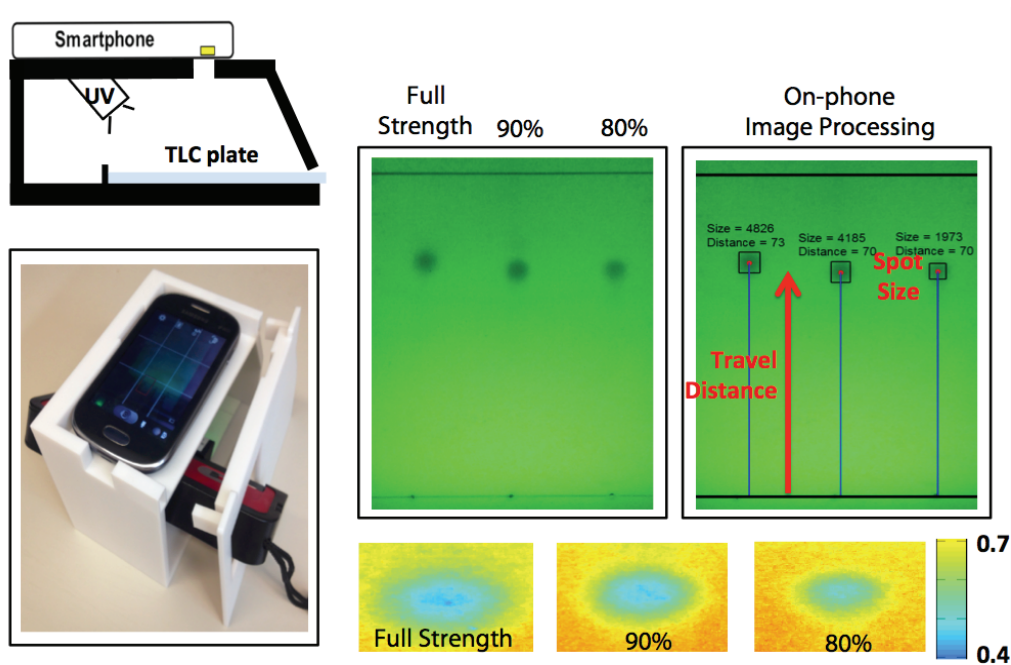
# Center for Innovative Instrumentation Technology (CiiT)

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## Smartphone Platform for Determining Prescription Drug Authenticity

Twenty-five percent (25%) of drugs distributed in Africa are counterfeit. CiiT researchers developed an innovative system that uses Thin-Plate Chromatography, a smartphone cradle, and a smartphone calibrated camera that determines the authenticity of drugs. This is a novel device/instrument for the life sciences. In addition to fabricating devices, the CiiT research group is also focused on the design, prototyping, and testing of biosensor instrumentation for high sensitivity, portability, and resolution.

Advanced instruments enable high resolution imaging of biochemical and cellular interactions. They provide the ability to monitor images of biochemical interactions as a function of time. Using the sensors and instrumentation, researchers are exploring new applications for optical biosensor technology including protein microarrays, biosensor/mass spectrometry systems, and microfluidics-based assays. All of these use nanoliter quantities of reagents. The methods and systems developed in the laboratory are then applied in the fields of life science research, drug discovery, diagnostic testing, and environmental monitoring.



*Smartphone Thin Layer Chromatography. An example of testing Amodiaquine, a malaria therapy. Image provided by Brian T. Cunningham, University of Illinois at Urbana-Champaign.*

## Center for Innovative Instrumentation Technology (CiiT)

The researcher has also developed label-free high throughput optical biosensor and readout instrument technology that uses nanostructured plastic surfaces. These are microreplicated from silicon master wafers. Applications include high throughput pharmaceutical compound screening, molecular diagnostics, PCR, electrophoresis, label-free microarrays, proteomics, environmental detection, and whole-cell assays.

A CiiT member, Management Sciences for Health (MSH), has a widely distributed team to develop effective controls to improve healthcare in developing nations. MSH has been deploying this breakthrough technique to identify and remove counterfeit drugs, thus improving healthcare.

**Economic impact:** Previous methods for counterfeit drug detection have required more expensive and complex equipment. The simplicity and reduced cost afforded by this breakthrough makes this work especially effective in developing countries where fraudulent drugs are very common.

Inspection of imported drugs at customs and distribution points can now more effectively identify shipments that appear legitimate but may have inadequate or fraudulent active ingredients.

This breakthrough will have significant impacts on actual drug availability, and as a result on actual clinical efficacy. It can be expected to contribute to reducing health care costs by helping assure that genuine quality drugs are available at the point of care.

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# Center for Identification Technology Research (CITeR)

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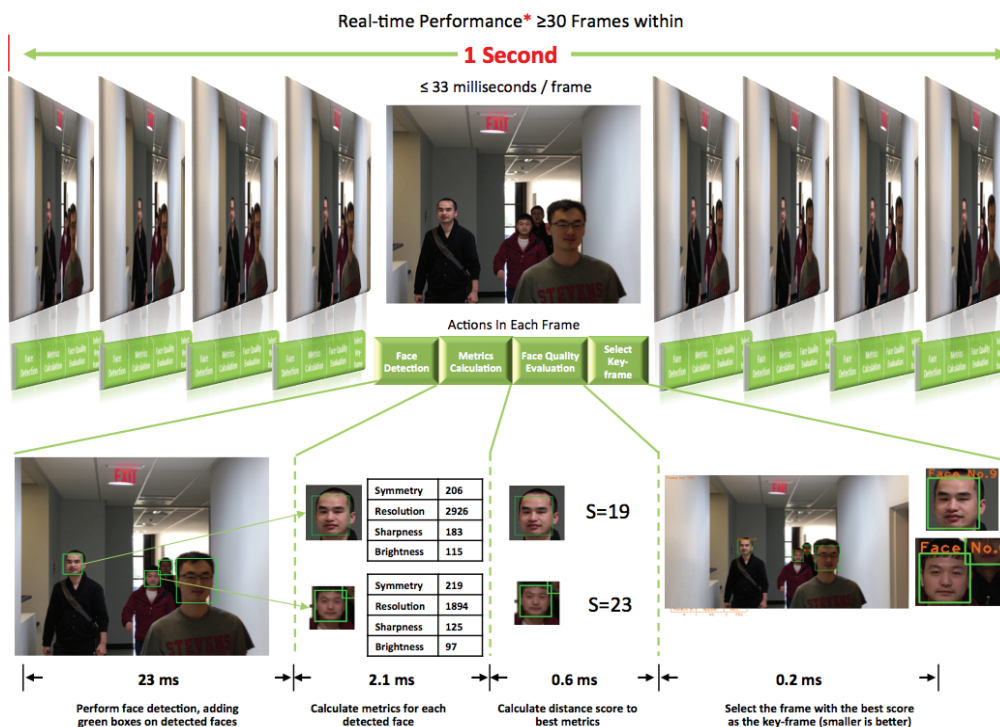
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## Rapid Recognition of Faces from Video

Recently the need for rapid recognition of faces in video has become increasingly important for national and industrial security. Facial recognition in video requires processing of huge amount of video streams using video analytics.



An innovative key frame analysis algorithm tracks the face(s) across video frames and, based on carefully selected metrics, automatically selects the frames to be used for face recognition. Image provided by Xuan Qi, Boyang Li, Yijun Jiang, Jiaju Huang, and Yan Gao, Department of Electrical and Computer Engineering, Clarkson University.

Considering video streams of 30 frames per second (FPS) from surveillance and security cameras, performing real-time face tracking on live stream video or on a large video repository already poses considerable computational challenges. Adding face recognition on top of this definitely complicates the situation. It often requires the computing power of a supercomputer or a cloud computing platform.

To address these challenges, CITeR researchers have developed an innovative key frame analysis algorithm. It tracks faces across frames and automatically selects frames with the best qualities based on carefully selected metrics. Researchers optimized the algorithm around a state-of-the-art graphic processing unit (GPU) as the hardware computing engine. The GPU is traditionally used for video display for computers, but it has better capability of performing parallel computation than do traditional Central Processing Units (CPUs). The team takes advantage of this capability, using it in their algorithm to accelerate face detection and image quality analysis to better meet the increased computational requirements. The team has demonstrated processing speeds of over 100 FPS; much greater than the real-time video frame rate of 30 FPS. Using a high-end GPU the breakthrough approach can be used for offline processing of large video repositories. It also can be used for online processing with a mobile GPU co-located with the video camera. This reduces the need to stream the entire video sequence to the back-end server for processing.

The face quality captured from the video stream has a huge impact on the face recognition accuracy. There has been extensive research on face matching algorithms based on still images. This research addresses how to extract the best quality face from video streams in order to improve the overall performance of face in video recognition system.

There are many application cases in which real-time processing of faces in video is needed. For example, face analysis in videos can be useful for solving crimes that involve video evidence. Airport terminals and railway stations all need real-time face detection and recognition to identify subject(s) of interest in a timely manner. Law enforcement agencies need rapid scanning of huge amounts of repository data searching for usable face images, whether for crime prevention or evidence gathering purposes. Industry and government affiliates are also interested in this technology for use in their operations. This project has been selected to be permanently on display as an active demonstration at FBI Headquarters.

**Economic impact:** For face in video recognition, the traditional approach is human-based. A human examiner goes through video streams looking for subject(s) of interest. This is the most labor intensive method; unfortunately, it is also very error-prone. Another approach is to go through the video frame one by one using computers. This approach can be suitable for offline processing but for large video repositories processing speed can be problematic. The third approach is to sample the video stream to select single frames for processing. This reduces the computation demand from that of the second approach. There is, however, no guarantee that the sampled frame can achieve the best results for identification purposes because the sampling is commonly based on the frame quality, not face quality, which is face recognition's primary interest. With this new key frame analysis algorithm and GPU accelerated technology, the aforementioned drawbacks can be avoided. The new approach can free human examiners from the tedious work of going through the video streams; the automated process takes care of that. This enables humans to focus on more important aspect of things, such as connection the crime dots together, or using the information to more quickly locate the suspect(s). All of this can decrease costs and make better use of the humans' capabilities.

The sensor system consists of both surveillance camera and mobile GPU. They can be widely dispersed to perform real-time face recognition in a distributed manner. For back-end processing of large video reposi-

tories using high-performance GPU based platforms (the computer with multiple GPU cards or a set of GPU-based computers) researchers can process large amount of video streams with blazingly fast speeds. This greatly improves the system's capability to identifying suspect(s) efficiently and effectively. It also significantly reduces labor cost associated with face recognition. The bottom line is that GPUs are a more economical way of computation when compared with traditional CPU-based technologies that have normalized computational capacities.

This would transform the current surveillance system from a passive system with the only purpose as recording video stream, to an active system that can detect suspect(s) in real time, putting face recognition at practitioners' fingertips. Finally, the point should be made that when deploying this technology, caution should be taken to protect the privacy of general public.

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# Center for Particulate and Surfactant Systems (CPaSS)

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## Targeted Removal of Stains by Cleaning Products

Surfactants, builders, binders, bleaching agents, and enzymes are different classes of compounds used in detergent systems. Differences are due to their physicochemical properties. Surfactants are versatile because their chemical structures consist of a hydrophobic (water-repelling) component and a hydrophilic (water-attracting) component. These allow them to interact with various chemicals in their surroundings. Surfactants also help to wet the skin and substrates. They facilitate soil removal and dissolution. In addition to surfactants, there are various other agents such as modified polymers and green surface active additives that aid in the removal of stains.

Factors that affect the washing performance of laundry detergents include the nature of the stains, soap structure and concentration, and the nature of active ingredients in soaps, water hardness, pH, and temperature. Some intricate stains result from personal care products such as deodorants which consist of various oils and metallic ions. Because of their complexity deodorants are not readily removed from fabrics by conventional methods. For such multifaceted stains, it is challenging to find the right balance of hydrophobic and hydrophilic constituents in cleaning formulations to achieve complete removal. The general objective of the research on cleaning products at CPaSS is to enhance stain removal by developing reagents targeted to destroy not only stains, smudges and dirt, but to elucidate the mechanisms by which stains are removed.



*An example of a household cleaning product.  
Credit: iStock*

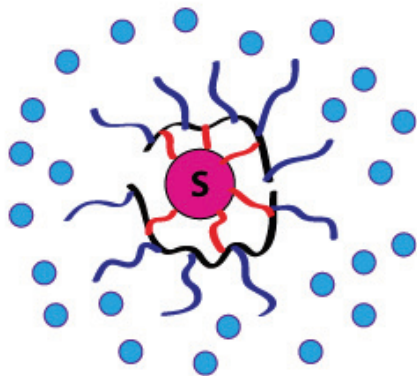
## Center for Particulate and Surfactant Systems (CPaSS)

Systems that CPaSS researchers investigate for optimal stain removal performance include surfactants, polymers, hydrophobically modified polymers, and enzymes explored. Incorporation of the stains into microdomains of surfactant supramolecular structures is an effective way to solubilize the normally insoluble substances. Researchers have learned that the performance of surfactants and their synergistic/antagonistic interactions with other components in detergent systems definitely impacts the effectiveness of stain removal.

Recent work at CPaSS has focused on developing correlations between the chemical structure and properties of reagents and their performance. During this process, researchers have developed mixed surfactant systems and hydrophobically modified polymers that form stable aggregates capable of effectively removing and solubilizing both oily and particulate stains. In addition, they also found synergistic interactions between a group of nonionic (no electric charge) surfactants and detergent enzymes by investigating enzyme functionality and dynamics using experimental methods and computer model simulations. This combined with investigations of green surfactant alternatives to existing chemical formulations are useful for optimizing environmental sustainability.

This research has many important applications ranging from consumer home care and personal care products to industrial applications. Since surfactants, polymers, and enzymes are used widely in industry, this research impacts the consumer product sectors of home laundry and surface cleaning and personal skin and hair care. The work also impacts the industrial and business sanitization (restaurants, hotels, schools, airports and hospitals) and the mineral and petroleum extraction sectors. Depending on the sector needs, CPaSS research helps identify ingredients to use and how they should be formulated in order to develop and manufacture more effective cleaning products.

By 2017, the global sales of household cleaning products are predicted to reach \$147 billion. All have significant positive economic impacts. Enhancing efficiency by increasing cleaning products' performance while lowering the necessary dosage of cleaning actives by using improved reagents and formulations of cleaning agents, will reduce production costs for industry and make them the products more affordable for consumers. More efficient formulations will allow lower water and energy usage. The amounts of chemical discharge into waste water will be decreased. This will bring about environmental benefits. Hence, the knowledge gained from this CPaSS research on enhancing formulations of existing cleaning products will bring about multifaceted economic benefits to the economy, improved sustainability, and higher consumer satisfaction.



*Solubilization of stain molecule (represented in the left figure as a pink circle with letter "S") inside a surfactant aggregate. Surfactants have both hydrophilic groups (represented in red) and hydrophobic groups (represented in blue). These allows them to isolate and solubilize stains as they are washed away by water (represented as light blue circles). Image created by CPaSS.*

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# Center for Pharmaceutical Development (CPD)

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## **Magnesium Stearate: Relating Physicochemical Properties to Functional Properties Such as Dissolution**

Researchers at the Center for Pharmaceutical Development (CPD) have been performing research to enable the pharmaceutical manufacturers make more effective tablets.

One of the most common ingredients in a tablet is magnesium stearate. Magnesium stearate is structurally similar to sodium stearate, which is better known as soap. This is used as a lubricant for the tablet press to ensure that the tablet releases properly after it is compressed. Its lubrication properties come from its fatty acid composition of stearates, palmitates, and other fatty acids.

Magnesium stearate is extremely difficult to study because it is both a complex mixture of chemical species and it can exist in multiple forms each of which have different properties. Compounding the situation is the fact that it is present in very low quantities in most tablets; making it even more difficult to study. CPD researchers have synthesized their own magnesium stearate so that they can both better understand how magnesium stearate's composition affects the tablet properties and also study how it changes form once it is compressed into tablets.

By understanding how magnesium stearate affects the tablet making process, companies can better predict how to add it into the mix, at what ratios, and what grades to get the optimal tablet without loss of product from malformed tablets and to make safer and better tablets that will help patients.



*Enabling manufacturers to make more effective tablets is the aim of CPD. Credit: iStock*

## Center for Pharmaceutical Development (CPD)

Magnesium stearate is an extremely problematic additive to study because of its complex nature and low concentration in a tablet. With the CPD approach of making our own magnesium stearate enables us to study it using advanced analytical techniques that have not been used to study it previously. Most importantly, we can now study what happens to the magnesium stearate when it is compressed into tablet form. When this is done it impacts both magnesium stearate's performance as a lubricant and the potential negative effects upon how a tablet dissolves.

The major beneficiaries of our research are the pharmaceutical industry. The ability to predict the properties of how magnesium stearate will perform in a formulation is crucial to making tablets reproducibly and avoiding potential product recalls. It will also speed up the development process by informing companies when their magnesium stearate supply changes, which can result in product delays.

**Economic impact:** Every pharmaceutical company seems to have a story where magnesium stearate caused a problem due to inconsistencies with suppliers or form changes that resulted in product failure. This breakthrough CPD research could have dramatic impacts on improving product quality through improved quantitative understandings of magnesium stearate's functional properties and, more importantly, how variations impact product performance.

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## Development of a Valuable New Enzyme, Amine Dehydrogenase

First and foremost, pharmaceuticals have to be efficacious, or in other words, they need to work to cure a disease or at least stop its progression. Next, however, pharmaceuticals have to be safe, and last, but not always least, they have to be affordable. Safe pharmaceuticals contain the active ingredient but no impurities. Affordable pharmaceuticals often are those that can be produced with a selective and inexpensive process.

Georgia Tech researchers at the Center for Pharmaceutical Development (CPD) have developed such a process for those pharmaceuticals that contain chiral amines, i.e., nitrogen groups. The FDA requirements around chiral active pharmaceutical ingredients (APIs) have become more stringent in recent years. Chiral molecules are non-superimposable mirror images, like handedness. Of these chiral compounds, chiral amines have had a particularly large and growing demand due to their high biological activity.

The Bommarius Research Team at Georgia Tech has met this demand with the noteworthy development of an amine dehydrogenase to an outstanding level. Not only has the group been successful in modifying an enzyme to produce this activity, but it has gone beyond an “academic” demonstration of this concept to provide an industrial-feasible and suitably applicable level of activity (rate of conversion) with this new enzyme’s capacity.



*Research performed may enable a less expensive process for drug production with fewer impurities.*

*Credit: iStock*

## Center for Pharmaceutical Development (CPD)

Multiple versions of this enzyme have been produced, thus creating a new class of enzymes that stand to enable a less expensive process to drug production, and a process with fewer impurities.

Previous methods of producing chiral amines chemically have relied on heavy metals, high-pressure hydrogenation, or crystallization. These operations are costly, hazardous, and not environmentally-friendly.

This breakthrough amine dehydrogenase route is capable of aminating numerous ketones with near perfect selectivity (handedness), making for a more efficient and greener route to produce these compounds. This work presents a viable alternative to the growing class of transaminases. Despite high levels of recognition, including the Presidential Green Chemistry Award, this class of enzymes has substantial disadvantages, such as the cost for the amine and incomplete conversion owing to an unfavorable equilibrium. While these challenges have been met with some level of success, there is a need to produce these chiral amines more efficiently by selective amination of ketones using free ammonia, which has been recognized as one of the most aspired enzymatic reactions previously unavailable by the ACS Pharmaceutical Roundtable. This route allows for increased efficiency and less waste.

This breakthrough has the potential to impact specialty chemicals with a particular emphasis on pharmaceuticals. It will allow for less expensive and more environmentally-friendly routes to chiral amines over the chemical synthesis.

**Economic impact:** The economic impacts of this breakthrough work will be both in cost-savings of production and in decreased use of organic solvents. It will simplify syntheses and creation of higher-quality product compounds. The potential impact is further exemplified by the tremendous interest in this project by center members. The vast majority of CPD member companies have prioritized this project as one of their top interests.

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# Cooling Technologies Research Center (CTRC)

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## Transient Liquid Phase Sintering Systems for Power Electronics

In microelectronic systems, referred to as integrated circuits (ICs) or computer chips, are bonded to circuit boards using low melting point metals. This makes it possible for electrical signals to be transmitted properly. When done properly, systems function well. Other important roles of low melting point metals are to transmit heat away from the computer chips, to prevent them from overheating during operation, and to compensate for mechanical stresses as different parts of the system heat up and cool down.

The operating temperatures of successive generations of computer chips have continued to increase with increases in performance requirements. An example of this would be the extreme operating environments for truck and car engines. As operating temperatures increase, low melting point metals are not strong enough to function. In addition, bonds between the outer surfaces of chips and cooling fins, which are typically formed by thermal greases, require more thermally robust materials as the operating temperature increases. Because of these limitations and challenges, enhancements are needed. This project is focused on designing innovative metal-based technologies and processes to replace low melting point metals, thermal greases, and other conventional thermal interface materials used for attaching components to circuit boards, silicon die to substrates, and components to heat rails and cooling fins.



*One class of end products for this research is in power electronics for new transportation systems, such as electric and hybrid vehicles. Credit: Toyota*

The approach we are using is known as "transient liquid phase sintering (TLPS)" in which a low melting point metal reacts with other materials in a joint to form a new phase with no remaining liquid, hence the liquid phase is "transient." In practical terms, a low melting temperature metal powder and an organic flux are mixed with high melting point alloys that are in particle form. These are applied to two substrates to be joined. When temperatures are increased above the melting temperature of the low melting point phase, a new compound begins to form at the interfaces between the liquid and the high melting point alloy and between the liquid and the substrates, as seen in the figure. For specific alloys, annealing temperatures, and particle geometries for the low and high melting temperature phases, the liquid phase will completely disappear, leaving behind a bonding material that has a significantly higher melting point than the original alloy. Having these new, more thermally stable bonding materials opens doors for even higher temperature and higher performance applications of electronics.

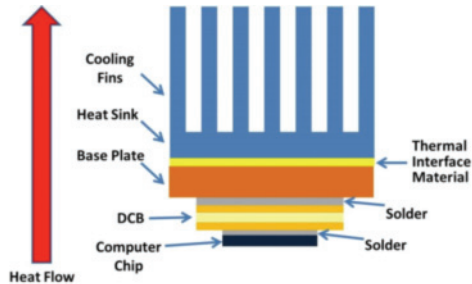
Formation of the intermetallic phase is not all that is required to make effective and reliable bonds. Current commercially available TLPS formulations exhibit high macro porosity and thus poor mechanical and thermal performance. CTRC researchers have identified seven key processes that must be considered to design an effective TLPS system. In this project we are developing and integrating models of the seven processes to identify composition and processing pathways to optimized TLPS technologies for specific high temperature and mechanical performance applications.

In 2014, this project developed models for the two most important processes for designing alloys. Researchers tested models containing as many as five elements and fabricated model paste formulations for attaching cooling systems to chips, semiconductor dies, and substrates in power electronics. The models are based on thermodynamic, kinetic, and technological analyses that answer the following questions: 1) What solids form when different elements are mixed together and heated? 2) Is there any liquid predicted to be remaining? 3) Can the process be accomplished in a practical time (< 1 hour) and at a temperature that does not damage the electronics? Answering these questions has led the team to innovative down-selection criteria and novel alloy formulations that work at higher temperatures where current commercial systems are unreliable.

The ultimate goal of this research has been and will continue to be to develop high performance and commercially viable thermal interface materials and bonding materials and processes based on transient liquid phase sintering. Our approach of integrating materials modeling and simulation, uses existing thermodynamic databases and tools, experiments designed to test and refine the models, and software tools for I/UCRC members to use for future TLPS application. It fits clearly within the Materials Genome Initiative (MGI) (<https://www.whitehouse.gov/mgi>). The MGI aims to double the speed at which we discover, develop and manufacture new materials through computational tools, experimental tools, digital data, and collaborative networks. One additional way in which this project works toward CMI goals is in correcting errors in existing public and commercial databases where the data has not previously been experimentally verified. In addition to its use in designing TLPS bonding technologies, the models may be useful for other solder-based technologies in which significant amounts of intermetallic compounds form, such as microbumps and in advanced memory devices.

**Economic impact:** The development of model systems and software tools represent key steps towards improved understanding and control of TLPS and bonding processes. In the last few months, CTRC researchers have formulated novel TLPS systems for a range of processing and use conditions. Preliminary experiments indicate that their bond strength is higher than existing TLPS formulations. The current highest priority is to quantify the mechanical and thermal properties as functions of TLPS composition, processing conditions, geometry, and temperature, and to

further refine the models. This research will benefit the electronics and automotive industries by identifying high performance, solid thermal interface and bonding materials for improved cooling of power electronics, particularly as operating temperatures increase.



*Schematic of electrical, thermal, and mechanical system needed for a computer chip to function. Solder and thermal greases play critical roles in heat flow from the chip to the outside air. Transient liquid phase sintering systems can replace both solder and thermal interface materials, increasing bond performance at higher temperatures needed for automotive and power electronics applications. Image provided by John Holaday, Purdue University.*

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## Thin Heat Pipes for Low Power Applications

Heat pipes are an industry-proven technology that offers potential orders-of-magnitude heat spreading performance improvements when compared to solid heat spreaders. The heat spreading efficiency of heat pipes reduces the overall power consumption of cooling solutions because auxiliary cooling components, such as axial fans (which dump heat to the ambient atmosphere) do not need to work as hard. While heat pipes are conventionally employed in larger-scale laptop and desktop computers, recent efforts within Purdue University's Cooling Technologies Research Center (CTRC) have focused on heat pipes that may be used in mobile platforms such as cell phones and tablets. The efficient heat transport that heat pipes enable is due to the phase change of an internal working fluid. It changes from liquid to vapor. Porous structures imbedded inside then passively drive the working fluid.

However, existing heat pipe design metrics focus on removing the maximum possible amount of heat from devices, rather than optimizing performance for operation at ultra-thin form factors. With the trend of decreasing thicknesses of mobile electronic devices, there is an unmet need to better understand the performance of heat pipes for these applications. Using analytical and numerical models, CTRC researchers have evaluated and compared the performance of thin heat pipes to that of a baseline commercial heat spreader.

This breakthrough CTRC work has generated comprehensive guidelines for the range of geometries and boundary conditions under which ultra-thin heat pipes may provide a comparative performance benefit against the current solid heat spreaders used in industry. A novel figure of merit was identified for the form factors and operating conditions of interest for mobile thermal management.

**Economic impact:** Heat pipes are ubiquitously deployed in consumer electronic products. Worldwide, smart phone shipments are expected to surpass 2.3 billion units per year by 2017. As a result, it is reasonable to assume that the economic impact of this breakthrough could be substantial. Intel, a CTRC member, recently launched a \$1.5M "platform thermals" research program through their University Research Office that is targeted at thermal management in this market. CTRC Faculty have been awarded funding through this program to further investigate transformational advancement of heat pipe technologies for ultra-thin mobile platforms.



*Ultra-thin heat pipe devices may enable higher performance mobile electronic devices that are cool to the touch. Image provided by CTRC.*

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# Visual and Decision Informatics (CVDI)

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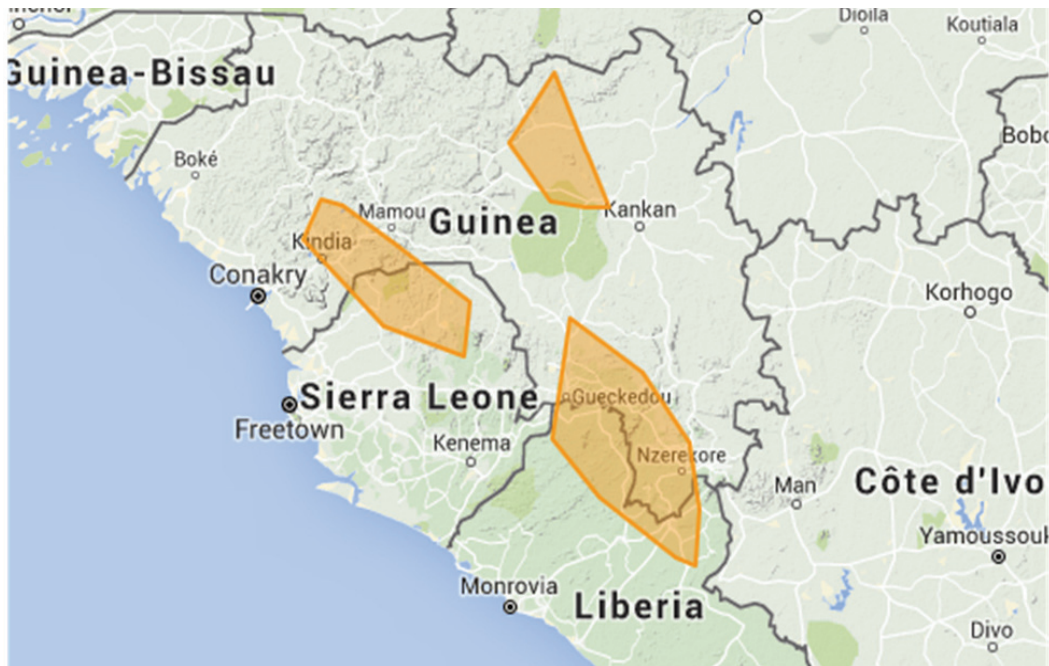
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## MapReduce-Based Spatio-Temporal Hotspots Detection and Prediction

Analysis of hotspots, referred to as spatial/temporal concentrations of abnormal activity, has broad applications in many areas important to daily living. These include epidemiology, disease surveillance, crime prevention, and environmental monitoring, to name a few. Understanding such critically important abnormalities helps identify the underlying causes of and appropriate steps for necessary action and possible remediation.

Researchers at the Center for Visual and Decision Informatics (CVDI) have developed a MapReduce-based framework spatio-temporal hotspots detection and prediction technique. It is based on a novel big data platform. Conventional hotspot detection methods use interpolation and tend to include non-hotspot regions. That can present problems. The breakthrough CVDI hotspots analytical tool is able to detect hotspots in a spatio-temporal context with a significant reduction in false positives - a major advantage.

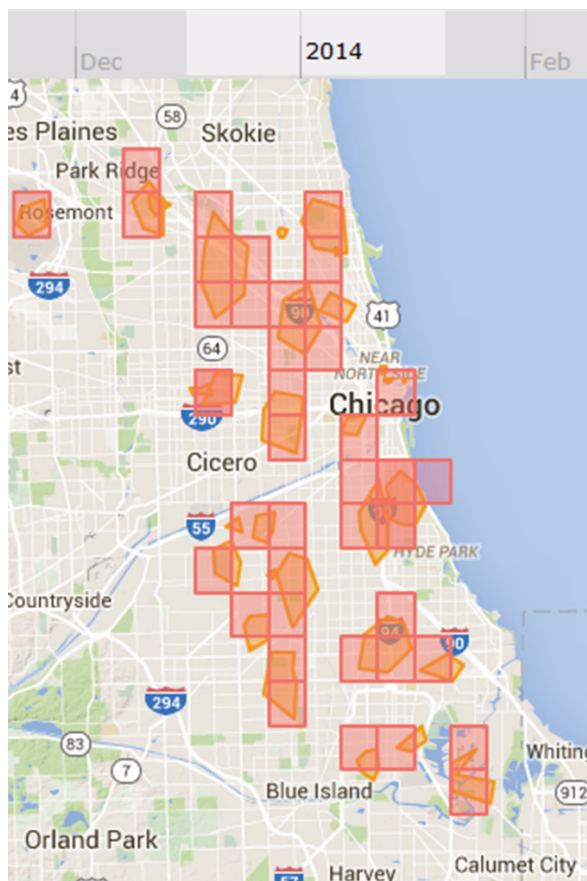


*Spatiotemporal hotspots of Ebola outbreak detected around May 25, 2014 in west Africa. Image provided by Jian Chen, Satya Katragadda, and Shaaban Abbady of CVDI.*

## Visual and Decision Informatics (CVDI)

CVDI researchers extended the algorithmic approach by developing a distributed version of polygon propagation based on MapReduce. This MapReduce-based framework uses a polygon propagation based approach to detect compact hotspots tailored to the region(s) of interest. Polygon propagation is computationally expensive. MapReduce is a programming model for parallel processing of large data sets on a cluster of commodity machines. During empirical evaluations, the MapReduce-based algorithm is capable of reducing execution time by as much as 90% compared to serial implementations.

This breakthrough uses an ensemble-based hotspots prediction module that leverages multiple prediction models (temporal, seasonal, spatial, and their combinations) for forecasting hotspots. The modeling is tailored to a local time series to predict subsequent spatio-temporal hotspots. This ensemble-based prediction approach also improved prediction accuracy by more than 10% over similar techniques.



Most prediction models for hotspots use techniques such as kernel densities or time series forecasting. However, using a single model to make short-term forecasts can be prone to problems. These are due to sampling variations, model uncertainty, and structure changes over time. This breakthrough tool overcomes these problems by using an ensemble-based approach that leverages multiple models to predict outcomes with different conditions that vary the outcome and parameters.

This hotspots analytics framework was tested on the 2014 West Africa Ebola Outbreak, on Louisiana Historical Contagious Diseases, and on Chicago Crime datasets. Results have been promising. Furthermore, social media, the proliferation of sensors, and other crowdsourcing mechanisms have provided unprecedented opportunities to observe and predict hotspots around the globe. These new modalities of communication and messaging have resulted in an explosion of data. The scalability and fault tolerance nature of the MapReduce-based analytics provides the ability to perform the type of large-scale machine learning that will become increasingly important in the future.

*Spatiotemporal hotspots of Chicago Crime in the first quarter of 2014, the underlying orange polygons are the detected hotspots and the red squares on top are predicted hotspots area based on previous historical data. Image provided by Jian Chen, Satya Katragadda, and Shaaban Abbady of CVDI.*

**Economic impact:** Spatio-temporal hotspots detection and prediction can have a wide range of applications in areas such as homeland security, diseases surveillance, crime prevention, and environmental monitoring. The potential economic impacts of the framework are substantial because in many domains it can be an efficient proactive decision support tool. More than \$3 billion of federal funds are spent annually on assisting state and local law enforcement in preventing crime. A severe contagious disease outbreak, for example, a pandemic flu, could result in a 5% reduction in the U.S. GDP, totaling \$675 billion in lost worker productivity and decreased consumer spending. This breakthrough helps law enforcement allocate limited resources to the right place at right time to prevent and minimize crime. It can also assist public health officials and environmental protection agencies to analyze real-time surveillance sensor data to detect emerging abnormalities and to prepare for what is likely to happen next.

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## Forecasting Influenza Occurrence to Improve ED Operations

Given how the virus strain changes every year and related environmental factors seasonal influenza forecasting is a challenging problem. Researchers at the Center for Visual and Decision Informatics (CVDI) developed a novel big data based real-time seasonal influenza forecasting technique projects titled "Visual Analytic Approaches for Mining Large-Scale Dynamic Graphs."

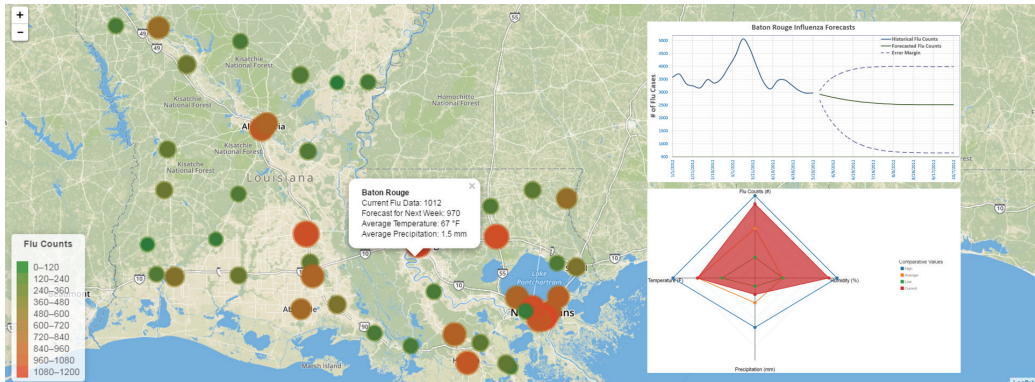
This novel influenza forecasting model that uses a two-stage vectorized time series model that captures the influence of local environmental weather conditions (based on frequent associations between the flu severity and weather conditions). It can be used to forecast patients visiting emergency departments for influenza type illness. To forecast future flu occurrences, the impacts of environmental conditions and spatiotemporal flu spread characteristics are integrated into the vectorized time series model.

The United States Centers for Disease Control (CDC) monitors weekly flu projections and provides data that is anywhere from a week to two weeks old. There are also several real-time flu surveillance systems for flu monitoring based on search keys from Google, and social media trends from Twitter. These models only provide real-time monitoring capabilities rather than forecasting.

There is considerable evidence in literature about the influence of environmental factors (temperature, humidity, precipitation) on influenza virus survivability, and patterns of spread in space and time. However, the influence of environmental factors had not previously been captured adequately for real-time forecasting of influenza. The resulting model from CVDI researchers outperforms much better accuracy performance compared to existing time series based influenza forecasting.

The seasonal influenza forecasting model that was developed from this research is currently being adopted by the Schumacher Group. The influenza prediction model will be used to forecast emergency department visits for influenza type illness. It is expected to be deployed across the 130 emergency department facilities in the United States that the Schumacher Group manages. The predictive analytics capabilities of this model will help Schumacher Group and their partnering hospitals to better manage emergency department resources, to better staff emergency department facilities, and to more effectively allocate resources.

**Economic impact:** The ability to accurately predict influenza volume contributes to the organization's ability to prepare for staffing and other operational impacts. Proactive resource management impacts hospitals' abilities to make most efficient use of its resources, including providers. Given the high percentage of expenses in emergency departments (EDs) that are associated with direct provider cost, modest reductions to provider cost can be expected to result in significant and positive impact on ED operating costs.



*The dashboard shows flu map for the state of Louisiana, flu forecast for the city of Baton Rouge (top right) along with environmental conditions including temperature, humidity and precipitation at that time (bottom right). Image provided by CVDI.*

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# Cyber-Physical Systems for the Hospital Operating Room (CyBHOR)

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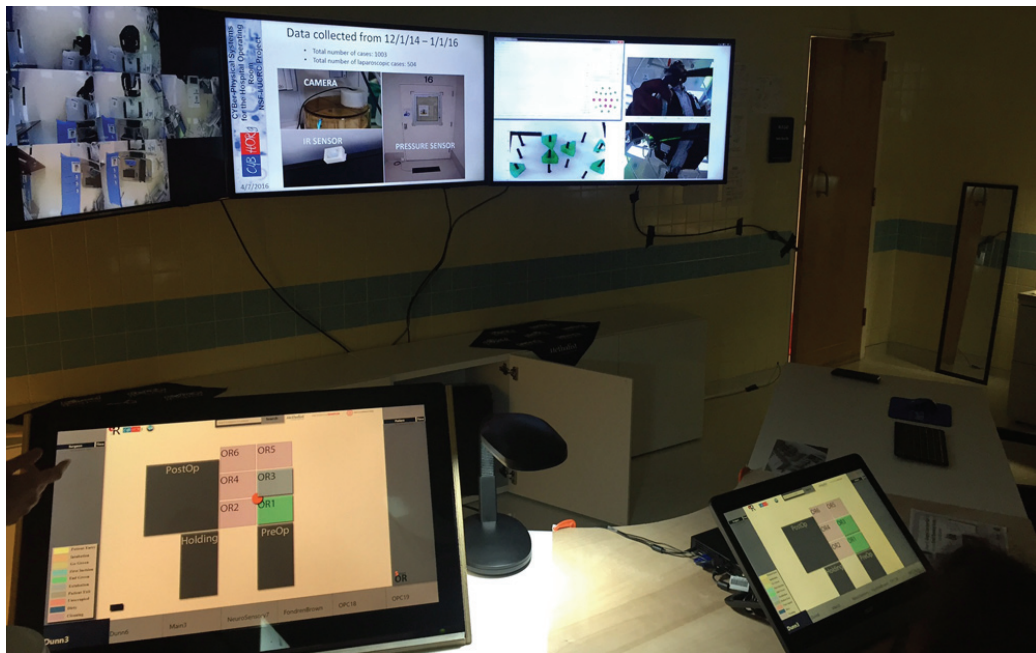
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## Coordinated Operating Room Network: A Path Toward an Artificial Intelligence System

Time in the operating room (OR) is one of the most significant budget items in modern hospitals. Importantly, it been shown that delays in operating room (OR) procedures due to mix-ups and lapses in scheduling and/or resource availability account for countless surgical delays and a significant number of post-surgical complications.

Optimizing management of multiple hospital operating rooms (ORs) is an extremely complex proposition. In every hospital, but especially in a large hospital like Houston Methodist that has more than 70 active ORs, staff must schedule and coordinate an enormous number of different procedures per day in each OR. Complicating the situation is the fact that because patients can differ so much, even common procedures can require significant variations in amounts of time required for the procedure.



*An example of the CORNET artificial intelligent (AI) system collecting data from operating rooms.  
Image by Craig S. Scott.*



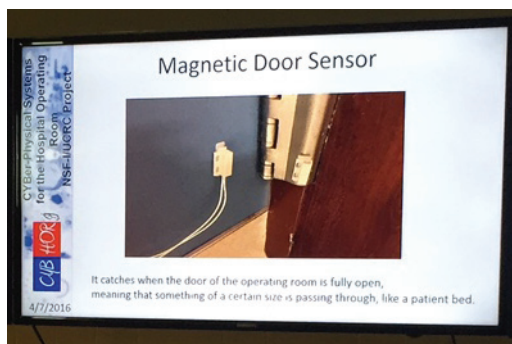
## Cyber-Physical Systems for the Hospital Operating Room (CyBHOR)

This breakthrough known as the CORNET artificial intelligent (AI) system, offers an innovative, cost-effective hardware/software OR awareness solution that: 1) detects what step of a given procedure the OR staff is at; 2) determines if steps are out of order; 3) identifies procedural delays, irregularities and unused OR time; 4) recognizes missed steps, and; 5) assists in root cause identification, analyses and assessment.

Optimal OR scheduling methods assume specific lengths of surgeries based on the procedure being performed and do not take into account differentiations in medical teams' performance. The reality is that each specific OR procedure requires gathering a complex and multi-skilled team led by a surgeon for a specific block of time; often for differing amounts of time for the same procedure.

The other unfortunate reality is that too often surgical procedures need to be either delayed or canceled because previous procedures have taken more time than expected and/or they did not start on time in the first place. Consequently, surgical teams can cause conflicts of space and time that had been reserved for other scheduled procedures.

This centers' team of researchers has developed an agent-base mathematical solution that reintroduces the human factor into the equation. The OR/AI system takes into account multiple factors from several levels of the hospital organization. It automatically informs what become, in essence, smarter OR units. It does so unobtrusively, without getting in the way of the functioning of surgical teams. The model is capable of providing better informed recommendations for improving OR management in real time, and timely early alerts when decisions to adjust and adapt are needed in order to improve scheduling and/or minimize delays.



The model OR/AI system was designed by an inter-disciplinary team of applied mathematicians, computer scientists, electrical engineers, physicians and nurses. Because it improves the processes of OR management, both patients and staff should benefit from a more efficiently run, more user-friendly OR systems that provide fairer and less biased assessments of situations as they develop and subsequent needed actions.

*Image by Craig S. Scott.*

**Economic impact:** It is generally accepted that one minute in the OR costs about \$100. In 2014, the OR management product market was estimated to be about 2.7 billion. It has been projected to expand to 4.5 billion by 2019. Our CORNET artificial intelligent system could be compared to an air traffic control system, managing multiple ORs, surgical teams, increasing efficiencies, improving patient outcomes and stakeholder satisfaction in real time.

CORNET artificial intelligent (AI) system is centered on patient and stakeholder satisfaction, health sustainability, and safety. The cost of deploying this system is predicted to be about \$10,000 per OR per year. Our conservative estimate is a 10% increase in OR efficiency, which for a block of 20 ORs would result in an addi-

### **Cyber-Physical Systems for the Hospital Operating Room (CyBHOR)**

tional 800 surgeries per year. As a result, this advance has the potential to make possible substantial enhancements to patient care and increases in revenues for the hospital. Furthermore, increased efficiency and more dependable OR schedules would result in decreases in staff overtime, leading to additional cost savings for the organization. Though almost impossible to estimate, the saving that could accrue from reducing post-op complications would be one of the most important aspects of this innovative work. The estimated ROI could easily be in the range of 1:50.

ORintel (LLC), a CyBHOR spinoff, is taking on the challenge of bringing this cost-effective solution to market.

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## Design Analytics Systems

The Customer Service Life Cycle (CSLC) system describes services that a medical device user/customer receives throughout a product's lifecycle. Medical device lifecycle stages include: requirements, acquisition, ownership, and retirement. However, most current design analytics systems ignore the costs associated with ownership and retirement. Maintenance cost, for example, is considered a primary cost of medical devices but they are often not captured in the current practices. These costs, however, are usually hidden within the activities of processing and reprocessing the devices.

One of the main challenges to mechanical systems, including reusable medical equipment, is identifying the relevance of cost factors of maintenance activities for specific devices. It requires significant research to extract related maintenance cost factors from devices' unstructured databases. Forecasting additional costs for system acquisition using design and process characteristics also requires significant research. It is also a challenge to identify implicit relationships between the device and equipment lifecycle factors of maintenance, acquisition, ownership, and retirement.



*Potential use of this outlier detection algorithm could enhance medical equipment evaluation and analysis, for example, in an endoscope. Image provided by Center for eDesign.*

To extract needed cost factors from unstructured data repositories, this breakthrough systematically identifies relationships between design, process characteristics and cost factors. This is achieved by first defining the taxonomy of design and process characteristics, then finding the explicit and implicit cost factors within historical data (which is potentially linked with design and process characteristics). Learning algorithms are being developed by eDesign researchers to improve device costs prediction by more fully understanding relationships between the factors.

Proper medical equipment repair history can reside in extremely complex sets of multivariate data. These contain both continuous and categorical variables. Hence, a variety approaches are required in order to adequately model these the variables in order to analyze the maintenance history data. To improve the safety and reliability of the medical equipment eDesign researchers identify abnormal cases, such as high frequency and cost of maintenance. They accomplish this by detecting outliers. In general, outliers can be detected using distance-based clustering algorithms. Algorithms like Attribute Value Frequency (AVF) and Outlier Detection for Mixed Attribute Datasets (ODMAD) are applicable for both continuous and categorical variables. For instance, endoscopes are one of the most widely used equipment in medical facilities. The Customer Service Life Cycle (CSLC) system found from data that a purchased endoscope used for surgery high cost repairs. As a result, the expected life of an endoscope is relatively less compared to microscope. To validate this conclusion researchers used an actual repair history dataset from non-profit medical facilities. Use an outlier detection algorithm to enhance medical equipment evaluation and analysis. Results should be applicable to any company or organization that uses devices that require significant processing and reprocessing (e.g., medical and hospice facilities, remanufacturing companies, equipment reprocessing companies).

**Economic impact:** The web-based design analytics system for developing and sharing medical equipment's total cost assessment information can potentially support purchase and retirement decisions and other comparative analyses. Trends from recorded traces of device maintenance, replacement, failure, and other incurred costs can be analyzed and displayed in the developed design analytics system. This system provides two modules: 1) a module for activity based costing from text analysis and data mining that extracts cost information from legacy data warehouses, and; 2) a visualization module to provide users with a conceptual understanding of the attributes associated with the decision information. This information is useful for medical device tactical acquisition, use and strategic planning.

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# Center for Energy-Smart Electronic Systems (ES2)

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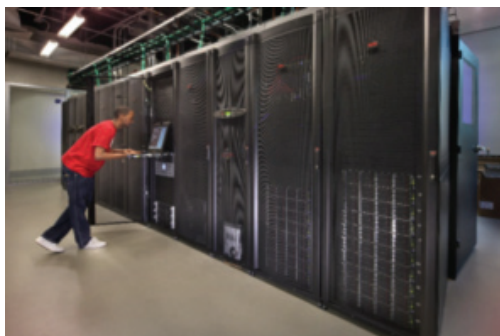
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## Putting Data Centers on a Diet: Dynamic, Load-Dependent Rightsizing of Server Capacity

The past decade has witnessed unprecedented growth in the number, size and capacity of data centers that support our daily lives domestically, in commerce, and in governance. Data centers represent the backbone of cloud computing. This is the core infrastructure that supports social networking, provide web services that we access daily from computing devices at all scales, from cell phones to desktops. Data center deployments are growing worldwide at unprecedented rates and scales. U.S. data centers consume about 100 billion kilowatt-hours of electricity annually. Data centers use electricity not just to run the IT equipment but also to power cooling systems that take away the heat dissipated by the servers. They stress out our already taxed power generation units. Unfortunately, current data centers are not very energy-efficient. Significant amounts of energy are wasted in operating data centers.



*Image of a data center, provided by ES2.*

Data centers are usually designed to target the peak demands but such demands rarely occur. However, data center operators tend to keep all servers online, so as not to miss any requests should the request volume go up suddenly. This practice results in idling servers or servers running at low utilization. These practices lead to low energy efficiency because idling servers dissipate a significant amount of power. An industry-wide study done by the Gartner Group indicates that, on the average, server utilizations are at less than 15% of their maximum capacity.

In the data center industry, a great deal of effort has been spent to reduce inefficiencies in cooling systems. As a result, the energy spent on cooling in today's newer, relatively well-designed data centers is less than 30% of the total power drawn by the data centers. The bulk of the remaining energy is spent to support the IT equipment. Significant energy savings are possible by better managing server capacities in ways that track demand as it fluctuates from one instant to the next.

## Center for Energy-Smart Electronic Systems (ES2)

This breakthrough ES2 technology automatically provides just the right amount of server capacity needed at any time to handle current offered loads and activates additional servers when the demand grows. This saves power by shutting down servers when demand drops. The improvements in energy efficiency comes from two main practices. First, active servers are operated at high utilization levels; this improves the overall energy efficiency of the IT equipment in the data centers. Second, unused servers are shut off, avoiding any power wastage from idling servers.

The challenge in doing such automatic server capacity provisioning has to do with the time it takes to activate turned-off servers when the load grows. Since it takes a few minutes to turn on a server, a reactive solution that reacts to increased request volume by turning on servers will not work, because increases occur suddenly and can exceed the capacity of the currently turned-on servers well before the servers being turned on are ready to accept requests. The ES2's breakthrough technology uses a proactive server activation/deactivation strategy that uses the recent history of the actual and offered load to predict the expected load to turn additional servers on in advance, avoiding any service degradation. Additional features permit the degree of cooling provided to dynamically match the capacity of the servers, thus avoiding wastage due to overcooling or damage due to undercooling. Demonstrations of a prototype implementation shows that the new technology permits over 25% reductions in data center IT equipment power draws in realistic scenarios of operation with almost negligible impact on performance.

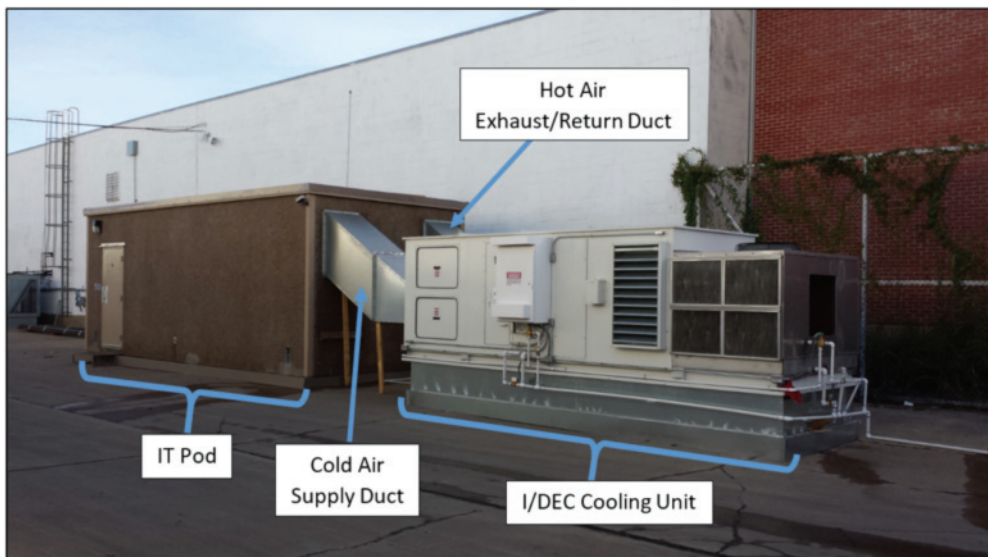
**Economic impact:** Automatic and dynamic server capacity provisioning in data centers, as enabled by this breakthrough technology, permit data center operating expenditures for the IT equipment to be reduced by as much as 25% without appreciable impacts on performance. Additional cascaded energy savings are possible in cooling system and in power distribution and conversion networks. The technology is particularly well suited to data centers that provide on-line services such as social networking, email, news, shopping, content searching etc. where the demands can fluctuate rapidly in volume. The resulting drop in electricity draw also lowers the dependence on fossil fuels and the carbon footprint.

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## More Efficient Data Centers: Maximizing Airside Cooling

Around the world, unprecedented and exceedingly large volumes digital data are stored in data centers. The data come from online transactions, social networking websites, banks, healthcare facilities, schools, government bodies, and industry, to name a few. It is essential that these data are reliably processed by and securely transmitted to a variety of user/customers. Within the last twenty years, the amount of digital data being generated has greatly increased resulting in ever increasing numbers of data centers.

Data centers house many servers with typically multiple thousands of IT equipment units. The centers require a considerable amount of cooling infrastructure to enable IT equipment to function properly. One way to reduce energy consumption of data centers is to use air-side economization (ASE) and indirect and direct evaporative cooling (I/DEC). These cooling methods do not use compressors, which is good because compressors consume large amount of energy to convert vaporized cooling fluid to liquid cooling fluid. Although not all data centers can be cooled 100% of the time using ASE and I/DEC methods, maximizing the use of ASE and I/DEC (minimizing compressor-based cooling system) can result in significant reductions in energy consumption of the cooling infrastructure. The annual number of hours ASE and I/DEC will be used in a year is expected to increase since IT equipment manufacturers have begun to make IT equipment that can be operated at wider temperature and humidity ranges than was possible few years ago.



*A modular data center. Image provided by ES2.*

Research on ASE and I/DEC for data center cooling has been conducted on a testbed modular data center. Although these methods of cooling are not new to data centers, maximizing their use over compressor based cooling technologies has the advantage of reducing overall cooling costs and carbon footprints. In the specific I/DEC unit that has been studied, a cooling tower is used to cool water that runs through a water-to-air heat exchanger (indirect evaporative cooling). For this system, the cooling tower can be



## Center for Energy-Smart Electronic Systems (ES2)

placed at a distance from the main cooling unit. This allows greater ease of maintenance and provides freedom to place the unit at a suitable place in the data center.

**Economic impact:** Electricity consumption by data centers is expected to increase from 91 billion kWh in 2013 to 140 billion kWh by 2020. Reliable operation in data centers of IT equipment requires that the heat generated needs to be continuously and effectively removed; otherwise, the IT equipment may fail to operate resulting in data center downtime. A recent study indicated that about 30% of total data center energy is consumed by the cooling infrastructure of data centers. Reducing energy consumption of the cooling infrastructure of data centers by few percentage points will translate to many thousands of dollars of savings per year in savings for data center owners and significant reductions in carbon footprints of the data centers.

This breakthrough cooling approach avoids the use of compressors or chillers. The approach s 70% less energy than traditional air conditioning systems. Depending on location and environmental conditions, water usage can also be significantly reduced in these systems. This is because water is recirculated and used several times. Continuous R&D testing has helped replace conventional propeller type fans with VFD to a more efficient EC axial fan in the cooling tower. Data centers that implement these cooling technologies will benefit from the electric cost saving. Overall, the cost of purchasing, installing and servicing an EC fan/motor assembly can save significant dollars as opposed to conventional fan/motor selections tied to a VFD.

The nation will benefit from more sustainable growth of energy efficient data centers that maintain smaller carbon footprints that conventional cooling systems.

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# Grid-Connected Advanced Power Electronic Systems (GRAPES)

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## Power Module Layout Synthesis (PowerSynth)

This power module layout synthesis tool takes a circuit description and produces a physical layout ready for manufacturing in minutes compared to the days and weeks required today by electronic packaging engineers. This breakthrough saves thousands of dollars in design costs and produces designs that operate more reliably and efficiently. This, in turn, leads to more efficient power electronic converters and motor drives. More efficient converters and motor drives translate into greater range for electric vehicles, better fuel efficiency of aircraft, more efficient environmental control systems for buildings, and improved energy efficiency in the electric power grid.

This breakthrough focuses on design automation. GRAPES researchers automated what is normally done by hand. The physical design of power modules normally takes three to four months by an expert by hand. This tool enables physical circuit layouts in only ½ an hour. The tool can also be used by non-experts to as a means to get them engaged in the design process.



*Electric vehicles will produce extended range with improved power electronics. Credit: Tesla*

### **Grid-Connected Advanced Power Electronic Systems (GRAPES)**

Stated simply, the end result of this design automation tool is improved electrical efficiency of power converters and motor drives. The work impacts many applications in the electric power grid, transportation, and building energy sectors. It also result in reliability improvements in all types of power electronics.

**Economic impact:** The main impacts are in the products that were mentioned above as being made more efficient and reliable. More efficiency electrical devices will certainly have many positive environmental impacts. The result of the tool itself is realized through a commercial software product. Currently, GRAPES is working with ANSYS to finalize the research.

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# Laser and Plasma for Advanced Manufacturing (LPAM)

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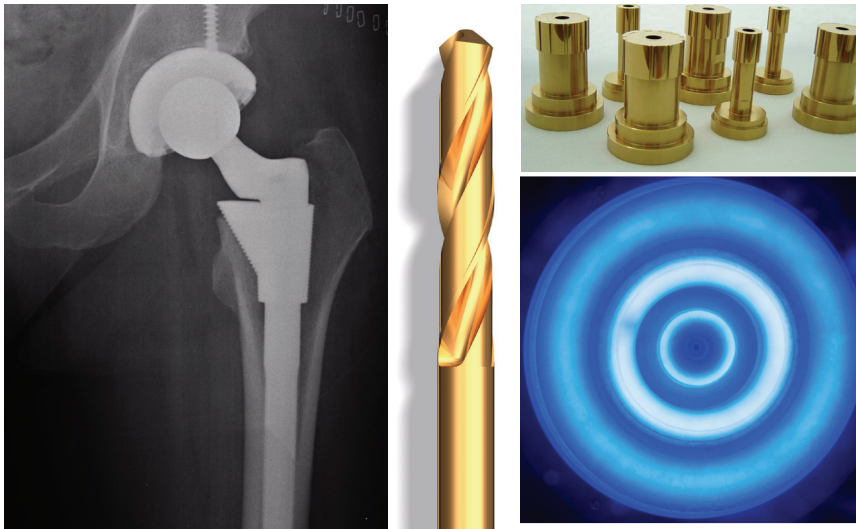
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## Symmetric Magnet Pack for High Power Pulsed Magnetron Sputtering

Demand for high quality, high performance coatings has increased dramatically over the last few of decades due to their application in diverse industries. The automobile, tooling, medical devices and kitchen appliance industries, to name a few, incur very high tooling costs related to performance improvement of coating processes. In recent years, advancements in magnetron sputtering technology have made huge impacts especially in areas like low friction, wear-resistance, corrosion resistance and hardened coatings. High Pulsed Power Magnetron Sputtering (HPPMS) or High Power Impulse Magnetron Sputtering (HiPIMS) is a relatively new and promising pulsed magnetron technology capable of producing high quality, high performance coatings that were not achievable by conventional magnetron sputtering technology.



*1. Hip replacement implants, coated by PVD. 2. A drill bit covered by PVD titanium nitride 3. Metal punches coated by PVD titanium nitride. 4. New magnet pack invented and produced by NSF-sponsored research which makes coatings at higher quality and faster. Images provided by David Ruzic.*

Currently, the throughput of this breakthrough technology is relatively low. Hence, additional research and development will be required to fully implement it commercially. With the development of the new TriPack magnet pack for HiPIMS by researchers at the Center for Laser and Plasma Advanced Manufacturing (CLPAM), deposition rates in HiPIMS process have been doubled. These deposition rates are directly related

## Laser and Plasma for Advanced Manufacturing (LPAM)

to the throughput of the processes. Therefore, coatings with 10x better performance than conventional sputtering techniques can be achieved in about half the time. By using these TriPack coatings, the cost of products that contain coatings can be brought down considerably.

**Economic impact:** This invention along with the HiPIMS technology should be important for optical coatings where the performance is always plagued by the time spent on the coating process. It has been demonstrated that improved coatings from use of the TriPack magnet pack with HiPIMS technology will achieve exceptional performance leading to longer life times and lower costs. In the tooling industry, drill bits and milling cutters are often coated with titanium nitride or other specially engineered coatings through conventional magnetron sputtering technology. These coatings increase their lifetime by a factor of three or more. With this breakthrough's new TriPack development in the HiPIMS technology, superior titanium nitride coatings with about 5x more life time can be achieved at 10% lower cost. Because of increased wear-resistance and lower friction properties, coatings on an engine's camshaft, for example, could help increase the efficiency of engine performance by reducing friction losses by 40%. A patent titled "Method of and Magnet Assembly for High Power Pulsed Magnetron Sputtering" (# 14/878,417) was filed as result of this work. The leading industrial vacuum equipment provider, Kurt J Lesker Company, has plans to sell this magnet pack commercially.

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# Net-Centric & Cloud Software & Systems (NCSS)

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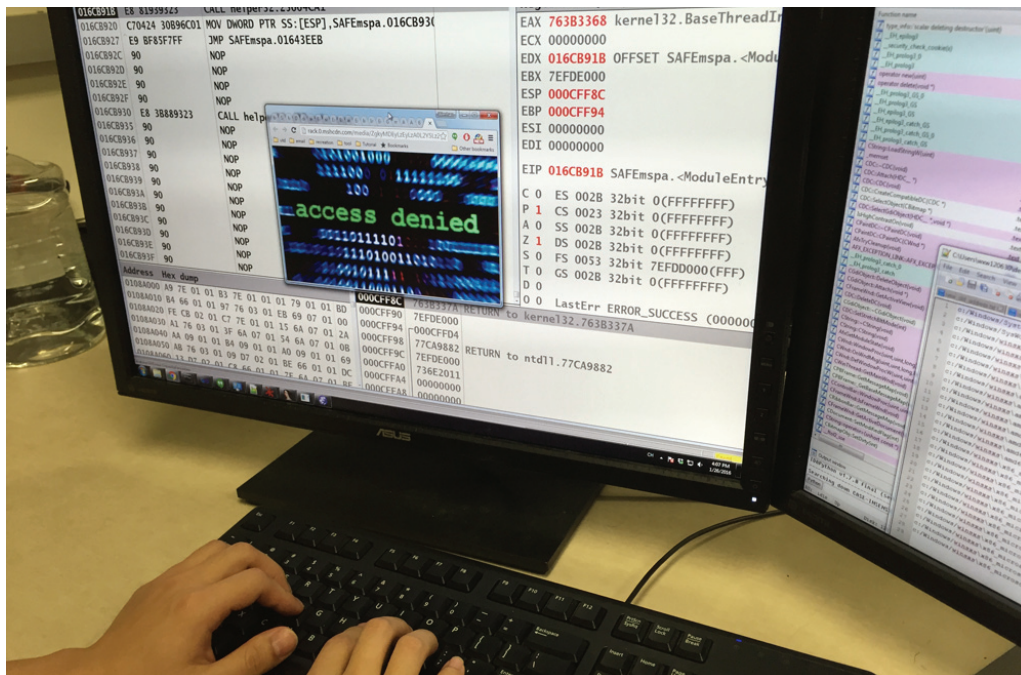
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## Protecting Against State-of-the-Art Cyber Attacks through Opaque Control-Flow Integrity

Opaque Control-Flow Integrity (O-CFI) is the first software security defense that merges binary software randomization with CFI to defeat one of the latest cybersecurity threats: implementation-aware code-reuse (IACR) attacks. IACR attacks hijack software by first exfiltrating in-memory code details of a victim program, and then exploiting those details to corrupt the victim program's control-flow paths. Such attacks defeat most CFI defenses, because CFI must typically enforce an approximation of the control-flow policy to maintain performance, and the attack's exfiltration step leaks the secret approximation to the attacker. Likewise, IACR defeats traditional randomization-based defenses, because the exfiltration leaks the randomized code layout.



Binary software security research being conducted at the University of Texas at Dallas. Image provided by Kevin Hamlen, The University of Texas at Dallas.

Opaque Control-Flow Integrity defeats IACR attacks by randomizing the policy approximation enforced by CFI in such a way that the secret approximation is confined to a protected data region of the software, not its code. This means that even if an IACR attack leaks the complete binary code, stack, and heap memory of the victim program to the attacker, this is not usually enough information for the attacker to reliably determine how the software's control-flows can be safely corrupted without raising an alarm. Attackers are forced to guess effective attack strategies. Such guesses have been shown to fail with astronomically high probabilities. Moreover, randomization ensures that even if one attack succeeds, the same attack fails against other instances of the program (or even the same program after it is restarted) because are all randomized differently.

Protections via O-CFI can be applied to secure software either at compile-time or to the already-compiled binary code. This makes this breakthrough approach extremely flexible; for example, O-CFI can be applied to secure binary software after it has already been shipped and deployed. This can be done without any aid from the software's original developers. In addition, its code transformations are fully automated, allowing it to be deployed almost instantly in response to emerging threats.

Opaque Control-Flow Integrity introduces the only known defense against an important class of zero-day cyberattacks. Moreover, it is extremely practical: It can be effectively implemented as a binary code transformation of existing, commodity software products, avoiding any need to re-develop the software or use any special tools in its creation. Experiments show that it introduces only 4.7% mean performance overhead on current processors, with even faster performance expected in the near future, since O-CFI's integrity checks are implemented using instructions that are expected to be hardware-accelerated on forthcoming x86/x64 processors.

O-CFI can be applied to protect most binary software products that are potential victims of control-flow hijacking attacks. These include web ecommerce systems, military systems, online database systems (e.g., healthcare information databases), industrial control systems, and other computing infrastructures requiring high assurance.

**Economic impact:** Since O-CFI can be applied to secure binary software that has already been designed, compiled, and deployed, it potentially mitigates the high costs associated with alternative security approaches requiring software re-development, such as penetration testing (e.g., fuzzing), source code review (which is notoriously ineffective at finding IACR vulnerabilities), or formal methods validation. It can also be applied much more quickly than these alternatives, potentially rescuing software from attacks that would otherwise have succeeded before more time-consuming approaches could discover and eliminate vulnerabilities.

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# Security and Software Engineering Research Center (S<sup>2</sup>ERC)

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## Scalable Modeling for Rigorous Software Specification and Testing

Modern software development processes for safety- and mission-critical systems rely on rigorous coding and testing to support dependability claims and assurance cases. The goal of researchers at Ball State University's Security and Software Engineering Research Center (S<sup>2</sup>ERC) is to economically provide for higher software quality and dependability for large and complex software-intensive systems.

'The two foundational methods, namely sequence-based software specification and Markov chain usage-based statistical testing, were developed in the 1990s by Jesse Poore and his colleagues at the University of Tennessee's Software Quality Research Laboratory. Since their inception they have been successfully combined and applied to a variety of industry and government projects. Field applications of these methods had earlier identified the need to address complexity and increase scalability both theoretically and practically for larger and more complex applications.

When these two demonstrably rigorous methods are combined and used in the complete software development cycle it translates to a formal system model that can be used as a first pass Markov chain usage model for statistical testing. However, to reduce the specification to a manageable size, the human specifier usually must clarify the extent to which inputs of the system can be partitioned into subsets that do not interact or communicate with each other.



*Selected case studies contain a range of embedded software from car door mirror electronic control units to satellite operations software. Credits: iStock*



This S<sup>2</sup>ERC breakthrough methodology overcomes this limitation by composing larger system models from smaller ones built on either disjoint or non-disjoint subsets of inputs. The constructed larger models form a basis for more rigorous automated statistical testing and software certification.

The Ball State research at S<sup>2</sup>ERC uses theory-practice-tools. As a first step they develop a theoretical foundation for the proposed approach. They then implement the theory and algorithms in a tool that supports sequence-based specification and defines the engineering process for how to accomplish it systematically with tool support. Finally, researchers conduct case studies to evaluate its applicability and effectiveness.

While previous work in this area focuses on a clean partitioning of system inputs that results in clean system decomposition to manage complexity and scalability, the new approach relaxes this constraint by looking into two ways to control the size of the specification and testing model. This is accomplished by either limiting the number of stimuli being considered or the number of states being explored. The new modeling techniques improve on previous strategies by working out a formal and systematic process to explicitly merge towards a complete system model. This results in render analyses for system level software specification, testing, and certification.

The completed work involves merging sub-models that focus on selected system boundaries. Researchers continue to work on combining partial work products that emphasize different applications. The selected case studies contain a range of embedded software from car door mirror electronic control units to satellite operations software. Results of the case study have shed light on when and how the theory is in effect in different application contexts to handle and manage specification complexity.

**Economic impact:** The consequences of an error or bug in new embedded systems or products can lead to product recalls, class action lawsuits, or wrongful death claims. Special efforts are in place to create products that more reliably perform as intended; not failing in the field is an essential quality. Though it is impossible to predict the extent of economic impacts that this development will enable, curbing the aforementioned consequences will save significant resources. This breakthrough demonstrates that scalable modeling for rigorous software specification and testing is not only feasible but practical. With a sound theoretical foundation and effective tool support, large and complex models of software-intensive systems can be more systematically constructed and tested statistically based on an operational usage profiles. This work has provided two distinct benefits: 1) more exhaustive analyses of systems' behavior in all possible scenarios of use prior to design and implementation, and; 2) more rigorous quantitative analysis after testing and validation prior to system deployment. Results can be used to more clearly demonstrate, document, and certify that systems are ready for their intended uses. The resulting scaled methods will prove to be better engineered, more dependable software systems, complete with audit trails of evidence to support claims related to the dependability for such systems.

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## A Trust Prediction Model for the Internet of Things (IoT)

The IoT paradigm promises to be a disruptive technology that will revolutionize our day-to-day lives. These IoT systems consist of dynamic networks of omnipresent "things", which are encapsulated as software services, which vary from refrigerators, thermostats, toasters, to baby monitors. As our dependence of such the IoT systems is expected to grow significantly in near future, the trust of such systems needs to be a major consideration and evaluated apriori.

Due to the time-sensitive nature of these IoT systems and the associated trust, predicting the trust of these systems before they are created is a research challenge that must be soon solved. This S2ERC research effectively addresses this prediction challenge by creating a trust model based on the principles of machine learning, service computing, software services and associated quality of service (QoS), and the context of such IoT Systems. This model advocates the "trust-by-construction approach" - where trust from the onset is an integral part of the design of such IoT systems. Preliminary results indicate that the proposed trust model is accurate and robust, and generalizable to many application domains.



*Learning thermostats are one example of IoT systems. Credit: iStock*

One of the factors that cause security vulnerabilities in the IoT systems is that systems are too often developed by composing many independently developed software services; some of which can be malicious and untrustworthy. A majority of the prevalent techniques used to compose these IoT systems consider neither the notion of trust from the beginning nor the context of the constituent software services. These approaches also, too often ignore the personalized trust requirements of end users. Although these assumptions do simplify the composition of IoT systems, in practice, the behaviors of "things" (and hence,

the associated software services) in IoT systems is highly depend on their contexts and on the personalized trust requirements of users.

The proposed model can assess trust of the individual software services and composed IoT systems and identify the minimum information required by each service to enforce better access control to sensitive data and detect anomalies. Furthermore, the proposed model will continuously adapt itself, in response to changes in the contexts of the IoT systems. It will also suggest alternative compositions with optimum QoS and functionality. Hence, this model will allow the developers of IoT systems to prune unwanted alternatives in the early developmental stages and will not only increase the confidence about these systems but also will reduce the associated costs.

Major benefits of this research will be for companies who are building or looking to build IoT systems by assembling multiple third party services. These IoT systems impact encapsulated software services. In such situations, ensuring that each IoT end point is safe and trustworthy is of paramount importance. This breakthrough trust model has the potential of helping several companies build a variety of IoT-based services and systems on top of a trusted security model that can deal with dynamic ensembles of "things." In addition, due to the strong theoretical underpinnings of this research, companies will be able to assess the trust of their IoT systems to obtain high confidence in their solutions.

**Economic impact:** One of the key factors to challenging the full potential of IoT is its security aspect. Because the scale of IoT is extremely large, the damages that can accrue due to IoT security flaws can be massive. Hence, a simple to use, yet highly secured IoT solution is a MUST to facilitate largescale commercial adoption of IoT. A step towards that vision is this validated trust prediction model. The model will not only enforce the "trust-by-construction" approach for developing the IoT systems, but also will conserve the design efforts by eliminating infeasible alternatives in the early stages of development cycles. In addition, a tool suite that employs this model will make the process of analyzing the trust of individual services and their ensembles semi-automatic, thereby, increasing the productivity of the developers and engineers. The pruning of inappropriate choices and automation will result in significant cost savings while developing the future generation of IoT systems.

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# Science Center for Marine Fisheries Science (SCeMFis)

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## Dredge Targets Juvenile Clams: Leads to More Sustainable Fisheries

A fundamental challenge in marine benthic ecology and fishery assessment is to quantitatively collect small infaunal (within the sediment) target species that have non-uniform distribution and/or low mean density (number per unit area). The surfclams and ocean quahogs of the mid Atlantic and Georges Bank regions, both of which support substantial fisheries with combined at the dock values in excess of \$50 million annually. These are prime examples of such species. Estimates of stock size are essential to responsible management of these clam fishery resources. Getting the estimates is made difficult by the longevity of the target species (30 years and >200 years, respectively, for surf clams and ocean quahogs) and the desire to demonstrate regular recruitment to the exploited stocks.



*(Clockwise for top left). The Dameron-Kubiak dredge on the port gantry of the Fishing Vessel E.S.S Pursuit. Juvenile ocean quahogs with between 10 and 45 mm shell lengths from dredge collections illustrate regular recruitment to the fishery resource. The variable bar space mechanism operates by elevating alternate bars in the floor of the dredge. High pressure hoses vent into the dredge body to wash catch and sediment in situ. Images provided by Roger Mann, Virginia Institute of Marine Science.*

## Science Center for Marine Fisheries Science (SCeMFIS)

Previously available sampling gear has been either grabs or cores that are limited in sample area. For this reason, there was a high statistical probability of missing target species because of low density; meaning lined dredges capable of covering large areas (integrating density) that produce high retention of accompanying sediment but damage target species. The lined dredge also presents other non-trivial challenges in deployment. Retrieval from a sediment-filled dredge can weigh several tons. This challenging winches and aboard ship resources that often result in marginal safety conditions for on-deck crew. SCeMFIS industry members designed and fabricated a research dredge that has variable bar spacing. This offers the ability to change the target size of species under examination. It also makes in situ sample washing possible by washing sediment from the sample as it is collected on the sea floor. This improves assessments of pre recruitment of fishery-sized clams.

The dredge design was finalized between March and May 2014, fabricated in May-July 2014, and tested at sea in August 2014. The design was a modification of a commercial hydraulic dredge that operated from a commercial vessel in water depths of 35-56 meters. A two-minute dredge tow at 3 knots sampled over 700 square meters of bottom - a three order of magnitude increased sampling area compared to traditional grabs or cores, thus allaying fears of missing targets at low density and underestimating stock size. The dredge performance exceeded expectations, providing high sample retention with little sample damage in a safer and tractable operating environment. The dredge was named the Dameron-Kubiak (DK) dredge after its designer (Captain T. Dameron) and lead fabricator (Mr. Kubiak).

The primary user of the DK dredge will initially be the National Marine Fisheries Service (NMFS), the federal agency tasked with fishery assessment and management under the Magnuson Stevens Fisheries Conservation and Management Act. The DK dredge was employed as a standard selectivity and juvenile survey dredge in the 2015 NMFS survey. It is anticipated to become a primary survey tool indefinitely into the future. Researchers foresee the variable bar spacing design used in the DK dredge being adopted globally for resource surveys in support of both fishery targeted species, and benthic communities in threatened or endangered ecosystems such as Arctic shelf ecosystems that support walrus populations.

**Economic impact:** Uncertainty in the assessment process of offshore clams, notably uncertainty of recruitment process, has been a concern in managing clam resources. The increased retention capabilities of the DK dredge have been a positive demonstration of more sustainable management of the targeted resources. When uncertainties exist federal regulators take extremely precautionary approaches when setting catch quotas; 40% reductions for the ocean quahog alone were considered - this could have amounted to > \$10 million annually in dock side value - several times more so in terms of overall economic impact, and possible loss of many jobs in both at sea and within portside sectors. Results generated by this breakthrough work with the DK dredge have removed much of the uncertainty that otherwise would have led to large quota reductions; thus negatively impacting both income and jobs. The DK dredge should continue to help fill the recruitment data gap, thereby increasing the accuracy of assessments, and stabilizing fishing quotas.

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# Smart Vehicle Concepts (SVC)

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## 3D Printing of Smart Structures with Embedded Optical Fiber Sensors

An optical fiber, which consists of a thin glass fiber coated with a plastic layer, allows light to be guided from one end of a fiber to the other with minimal loss light. Fiber Bragg Grating (FBG) sensors are a special type of optical fiber that measure local deformations, or strains, through deviations in a reflected wavelength of light. These extremely precise strain measurements can be used to monitor the internal condition of structures. To that end, FBG sensors are embedded in carbon fiber reinforced composites such as those used in aircraft frames, windmill blades, and high performance vehicles. The ability to embed these flexible and brittle sensors into metals has been limited until now.

This breakthrough investigates embedding FBG sensors into metallic structures through ultrasonic additive manufacturing, a recent 3D printing technology that uses ultrasonic metal welding to additively weld metallic foils. Since the process takes place at low temperature, there is no melting of the protective plastic coating on the FBG sensors.



*Aircraft actuation systems require embedded condition monitoring and load sensing devices. Courtesy of Moog Inc. and airline photo from iStock.*

## Smart Vehicle Concepts (SVC)

When an array of FBG sensors is embedded into a metallic structure, or into a hybrid metallic/non metallic structure, a seamlessly integrated sensing network becomes possible. Such networks are immune to electromagnetic interference, and are mechanically robust, non-invasive, and operate at high frequencies. The SVC research team has demonstrated the successful manufacture of test parts that have embedded FBG sensors. These were tested in static and dynamic conditions over a range of strains, frequencies of operation, and temperatures.

In this study, FBG sensors were embedded in aluminum 6061 using a high-power ultrasonic additive manufacturing system developed and manufactured in the U.S. by Fabrisonic, Inc. of Columbus, Ohio. The system is based on a computer numerically controlled milling machine that includes end mills for subtractive operations, a 9 kilo-Watt of power ultrasonic welder tool, a laser etching system, and a fully automated tape feed system for feeding metallic foils to the process. The ultrasonic vibrations generated by the welder head were used to scrub impurities and oxides away from the faying surfaces bringing metal to metal into intimate contact under high mechanical force to metallurgically weld the metals. A unique feature of the ultrasonic additive manufacturing process is that it takes place without melting of the metallic foils. The low process temperatures enable the embedding of glass, plastics, organic fibers and other materials without compromising their integrity.

Aircraft components are life-critical. As a result, methods are needed to monitor their structural integrity and functionality in real time. Traditional methods based on foil gages require redundancy to address failures created by electrical contacts, and cannot perform health condition monitoring inside of metals. This breakthrough changes this paradigm by making it possible to directly address these limitations. The applicability of FBG sensors is not limited to aircraft applications; other areas of use include rotating machinery, vehicle structures, and civil infrastructure.

**Economic impact:** In 2015, commercial airlines spent about \$50B on maintenance, repair and overhauls of aircraft fleets worldwide. An estimated \$65B will be spent in 2020. As aircraft systems become more complex and higher performing, along with the continuing need to make aircraft lighter and more fuel efficient, methods to improve the quality, reliability, and predictive ability of structural health conditioning systems are becoming ever more critical. Methods such as those of this breakthrough will bring significant savings to aircraft manufacturers, while also improving safety.

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# Wind-Energy Science, Technology and Research (WindSTAR)

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## Extremum Seeking Control for Maximizing of Wind Turbine Power Output



Wind power is a primary renewable energy source. Wind turbines are operated across a range of wind speeds. For a majority of the time, wind turbines operate below the rated wind speed; the so-called Region-2 operation. The primary objective of Region-2 wind turbine control is to maximize the power output by adjusting generator torque and/or blade pitch angle.

In field operation, WINDStar ESC Region-2 control strategy and wind turbine control systems face two major challenges. The first is coping with the not insignificant uncertainties and changes in turbine characteristics. These uncertainties and changes are due to the complexities of wind field and turbine aerodynamics, manufacturing variability, blade wear and the accumulation of foreign materials such as snow, ice, bugs and dirt. The second challenge relates to the fact that typical anemometers (air speed gauges) on commercial turbines do not provide the needed wind measurement accuracy and reliability that is necessary for optimal energy capture. This is due to the accumulation of snow and ice, wear, blockage and a phenomenon known as the near wake effect.

*A wind turbine. Credit: Wind Energy Development Programmatic Environmental Impact Statement (EIS)*



## Wind-Energy Science, Technology and Research (WindSTAR)

The major impact of this breakthrough WINDStar technology is increased energy yield without significantly increased cost. Referred to as Extremum Seeking Control (ESC), it has the ability to address these challenges because: 1) it is a model-free control strategy (that is, it is not sensitive to modeling uncertainty), and; 2) it does not require wind measurements. ESC is a self-learning algorithm that uses a probing signal (dither) to determine how to adjust the generator torque gain and/or blade pitch angle for maximizing power production in Region 2 wind turbine applications.

Currently available wind turbine controllers for Region 2 applications are usually based on pre-determined models, curves, or lookup tables; precise wind measurement is required. During field operation such strategies cannot optimize energy capture because of changing turbine characteristics and inaccurate wind measurements. Recently proposed adaptive control schemes alleviate the need for models, but may not be capable of decoupling the changes in wind input from that of the tuning of control inputs. This leads to excessively long times to achieve best performance. This implies that wind turbine owners would lose energy and the revenue it provides due to an inherent inability to track the point of maximal power production with adequate reaction times.

The WINDStar Center's ESC Region-2 control strategy uses an innovatively designed dither signal that serves as carrier for the information required to maximize power. This process is similar to the process used in AM radio transmission, wherein a properly designed carrier transmits useful information. In the ESC for power maximization, the most useful information is the "slope of the power curve," which allows the algorithm to decide how to climb this curve to its maximum. Thus, by demodulating from the carrier signal the slope of the power curve, power maximization is achieved despite wind fluctuations. As a consequence, the convergence time of the control parameters is greatly reduced.

The breakthrough WINDStar ESC Region-2 control strategy can be implemented in both new and existing wind turbines because the technology features a simple control structure and makes use of control inputs and measurements readily available on commercial turbines.

**Economic impact:** The procedure for ESC algorithm tuning is relatively simple. This makes relatively straightforward field commissioning possible. Wind turbine operators using ESC for power maximization will benefit through higher energy capture without significant increases in maintenance cost. As a result of this breakthrough the overall levelized cost of energy (LCOE) for wind power generation can be reduced, thereby increasing the value proposition for wind power.

Field evaluation of ESC at NREL's CART3 600 kW turbine has shown an impressive 12 to 17% increase in energy capture relative to common controllers without substantive increases in structural load. The economic impacts on energy producers and consumers should therefore be substantial. Based on the NREL test results, WindSTAR's industry members estimate increased energy output of at least 1-3% for actual field deployments of the technology. For a typical commercial scale wind turbine, a 1% increase in annual energy results in an extra \$3,000-5,000 per year per turbine. That is, a 3% increase in energy capture made possible by this technology will likely result in \$470-780 million increases in the annual revenue for the U.S. wind power industry even considering the currently installed capacity. This is a huge opportunity for any entity that operate turbines and should be very attractive to wind farm owners.

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