SMART

Scalable Manufacturing of Aware & Responsive Thin Films

SUMMER 2021

Table of Contents

SMART
Purdue University

Greetings from Professor Ali Shakouri

We would like to welcome both those who are learning about the Purdue SMART Films Consortium for the first time as well as our valued partners who help make this ecosystem possible.

SMART is a university–industry consortium dedicated to developing scalable low-cost sensors, Internet of Things (IoT) devices, and networking and communication technologies. As a cross-disciplinary team, we unify two dozen faculty across ten Schools and four Colleges. Our resources combine advances in roll-to-roll manufacturing and functional printing, as well as in electronic systems, data analytics, and artificial intelligence (AI), to enable widespread use of IoT and digital technology.

As described throughout this report, we partner with a range of industry sectors, conducting research that addresses their digital needs. Our research involves the whole vertical stack—from AI-enabled manufacturing, materials and devices, hybrid integration, and high-performance electronics to low-power communication, networking, and advanced machine learning. We have the expertise to help industry obtain reliable data from low-cost and unreliable sensors in a variety of real-world and noisy environments—healthcare, emergency response, agriculture, food, infrastructure, manufacturing, etc.—in the most cost-effective manner.

We are deeply grateful to our industry partners who provide critical funding and exciting research ideas, and who are invaluable collaborators throughout the projects. Our partners' participation fuels cutting-edge research that will ultimately advance the entire field.

Please enjoy reading our report and learning more about our exciting research. Contact me at your convenience with any questions.

Warmest regards,

Ali Shakouri
Mary Jo and Robert L. Kirk Director of Birck Nanotechnology Center
Professor of Electrical and Computer Engineering

For more information:
Prof. Ali Shakouri
Office: 765-496-6105
shakouri@purdue.edu
https://engineering.purdue.edu/SMART

Consortium Benefits

- Voting to prioritize consortium research initiatives
- Early access to research results, consortium IP, and prototype devices
- Top recruiting opportunities to students who work in interdisciplinary teams
- Access to consortium-developed short courses and weekly seminar series
- Access to Birck user facility next to Discovery Park District's innovation ecosystem
- Opportunity to define synergistic IP-protected projects

A

B

Z Orientation Process: A New Advantage in Manufacturing

For many decades, roll-to-roll (R2R) processing has provided fast, affordable, and reliable manufacturing. **Prof. Mukerrem Cakmak** (photo A), Reilly Professor of Materials Engineering and Mechanical Engineering, has advanced R2R by developing the Z Orientation Process, which has a distinct benefit upon expanding opportunities for producing reliable, high-volume, low-cost polymer films and sensors. It adapts external force fields, like electric and magnetic, to organize nanoparticles/phases along columns oriented in the thickness direction of films.

Z Orientation processes have been gaining interest in recent years by batch processes, but methods like R2R manufacturing were needed to accelerate market arrival. There are a number of technical challenges going from batch to continuous R2R process, but these were eliminated by Cakmak's patented process.

Current projects include:

- **Enhanced Piezoelectricity:** Cakmak is developing completely transparent speakers. Users will be able to enjoy music from speakers that appear to be a window. With this technology, haptic touch screens can be developed. Users experience a vibration or other indication when they apply force to the screen.
- **Piezoresistive Sensors:** Piezoresistive sensors are useful for high-resolution pressure mapping sensors. One such project being developed by Cakmak is seniors' shoe inserts. Users are alerted just before losing balance to avoid suffering a fall.
- **Healthcare:** Currently, Cakmak and his colleagues are working to develop a sensored belt to assist women with high-risk pregnancies. With Cakmak's flexible and lightweight sensors, the belt can be worn continuously to safely monitor both the health

of the mother and the child. The team is also developing a wound dressing that causes minimal stress on the wound by introducing anisotropic swelling and causing the dressing to swell away from the wound—reducing stress and promoting healing.

The R2R system is also being upgraded to include a variety of in-line characterization capabilities including confocal and capacitive thickness measurements, Eddy current and hyperspectral line imaging.

Predicting Costs, Saving Money, Helping Local Manufacturers

Prof. Jan-Anders Mansson (photo B), Distinguished Professor of Materials Engineering and Chemical Engineering, is working on Predictive Technical Cost Modeling (PTCM), which identifies the factors that drive costs on single manufactured parts, how these costs relate to manufacturing-specific parameters—and then what can be done to reduce those costs.

Mansson was motivated to develop PTCM to address an ongoing, key concern he recognized among the many major manufacturers he had collaborated with over the years, such as Daimler, VW, Hyundai, Toyota, Volvo, and Ford as well as major European Framework Research programs. PTCM is designed to optimize each production step as well as process lines in terms of manufacturing costs. With the support of Lead Network Engineer **Ben Haley**, Mansson's group conducts a detailed analysis of the materials, energy, and tool depreciation cost for the production of printed electrochemical sensors. Today, using existing tools, the manufacturing cost is approximately 10 cents per sensor, but by increasing roll-to-roll speed and production volume, cost per sensor could be reduced to a fraction of a cent.

One example of PTCM is a study Mansson's team conducted regarding the use of alternative production methods and material types to manufacture composite floor pans in a complex geometry indicative of a specific vehicle. Mansson's cost analysis of various manufacturing scenarios identified the dominant material cost as scrap material lost during manufacturing, rather than the type of resin or carbon fiber selected for use in the material. A full 18% of the composite material was lost to scrap during manufacturing, dominating the total cost of the part. Mansson's analysis led to recommendation of more automation of the manufacturing process to reduce the scrap. Even the higher cost of automation would be offset by the reduced scrap costs at high volumes required for automotive manufacturing, leading to lower overall costs.

"This system gives the manufacturer a critical tool for competitive insights," said Mansson. "We identify key cost drivers, such as materials, utilities, labor, capital costs of equipment, tooling, and such. Then we determine the contribution of each of these drivers to the total cost for a single manufactured part and how those costs scale with production volume, return of investment, etc."

Mansson is also the Co-Director of Indiana Manufacturing Competitiveness Center (IN-MaC), which includes his Manufacturing Design Laboratory (MDLab) and the Indiana Manufacturing Institute (IMI) testbed. The MDLab testbed for composites is integrated with the IN-MaC and its overall smart factory testbed, giving it a large range of Industry 4.0 capabilities. IoT devices and sensors from Birck are integrated at the IMI testbed and they provide real-time feedback about the vibration spectrum, temperature, electricity usages, and machine parameters. This set up is being replicated at local manufacturers throughout the surrounding 10 counties.

Additional Research Team Members

FACULTY

Gary Cheng: Prof. of Industrial Engineering and Materials Engineering

George T. C. Chiu: Asst. Dean for Global Engineering Programs, Prof. of Mechanical Engineering

Tian Li: Asst. Prof. of Mechanical Engineering

Jianguo Mei: Assoc. Prof. of Organic Chemistry

Arvind Raman: Executive Assoc. Dean of College of Engineering, Prof. of Mechanical Engineering and Prof. of Materials Engineering

Ali Shakouri: Director of Birck Nanotechnology Center, Prof. of Electrical and Computer Engineering

Alexander Wei: Prof. of Organic Chemistry

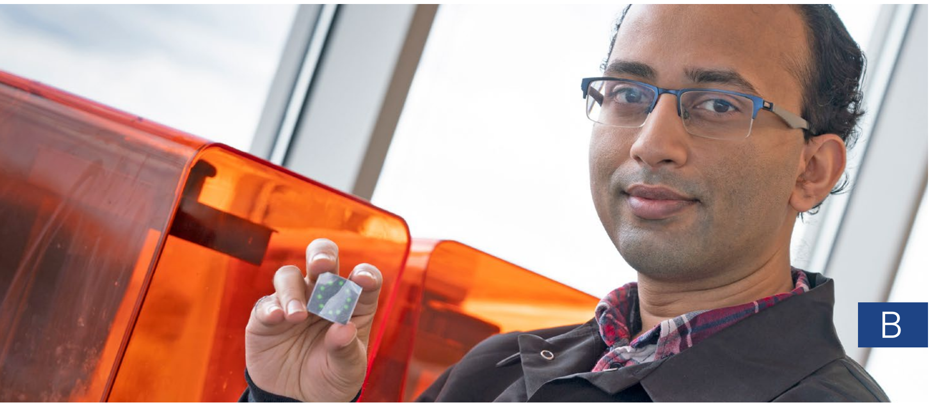
Jeffrey Youngblood: Prof. of Materials Engineering

STAFF

Nicholas Glassmaker: Research Scientist

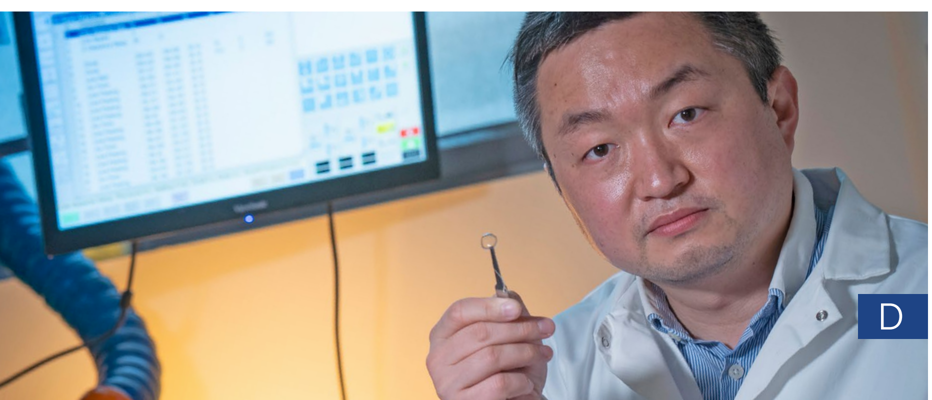
Ye Mi: Research Scientist

A



B

C



D

Stopping Outbreaks Rapidly, Affordably

For viruses, there are few defenses as effective as rapid testing. There are two labs within the SMART Consortium that are developing new, affordable sensored technologies to rapidly detect viruses.

Prof. Lia Stanciu (photo A), Associate Head and Professor of Materials Engineering, has developed an electrochemical platform detection technology to address a range of dangerous, quickly transmitted viruses. "This pandemic has highlighted the need for printed sensors to help with early detection," said Stanciu. "We can identify outbreaks earlier and stop them in their tracks."

Stanciu's electrochemical platform is a home-based COVID-19 test whose results are much more accurate than the rapid testing devices currently on the market. With this self-administered test, users simply place a saliva sample into a small reader, and then results appear within minutes. The user can also opt to connect the reader to a smartphone, where the results are displayed and even stored on a smartphone app. A partner company, IdentifySensors Biologics, is currently translating the device for the marketplace.

Another member of the SMART Consortium, **Prof. Mohit Verma** (photo B), Assistant Professor of Agricultural and Biological Engineering, has developed a small, paper-based sensor that, when placed in a portable heating device for just 60 minutes, can provide rapid but critical answers.

"We have developed a platform technology that can address multiple challenges," said Verma. "It is very versatile, easy to use, and effective." This platform technology includes a Bovine Respiratory Disease (BRD) test. BRD affects 15-20% of beef and dairy cattle, causing losses of almost $1 billion per year. Verma has developed a nasal swab test that is uniquely effective due to its ability to identify the most likely pathogens causing BRD. With this information, this test can:

1) increase the likelihood of an accurate initial diagnosis;
2) reduce the cost of treatment;
3) expedite recovery times; and
4) reduce excess use of antibiotics.

The test is now being commercialized through Verma's company, Krishi.

Verma's lab worked rapidly with Raytheon BBN Technologies and several other collaborators to successfully develop its paper-based sensor to test saliva for COVID-19; it is now expanding its test for influenza. According to the Centers for Disease Control, between 3% and 11% of the U.S. population get infected and develop flu symptoms each year.

Protecting Food, Saving Lives

SMART Consortium researchers are approaching food safety throughout critical paths of the food chain. This work addresses a critical need, since 47.8 million people in the U.S. suffer from domestically acquired foodborne illnesses. Sadly, 127,839 people are hospitalized and 3,037 die annually.

Verma has developed a platform technology in which a small, paper-based sensor is placed in a portable heating device for just 60 minutes. His current focus is upon agriculture. In the case of fresh produce, two key risk assessments facing every farmer are: 1) Where should I plant my crops to avoid contamination? and 2) Is my harvest safe? Funded by the Center for Produce Safety, Prof. Verma is adapting his paper-based sensor to these questions, providing risk-assessment tools to farmers as well as improving overall food safety for consumers.

Stanciu has developed a colorimetric platform, which is a paper-based device that rapidly changes color when it comes into contact with a positive sample. This device, which is being developed with Purdue's Center for Food Safety Engineering, will successfully identify foodborne pathogens such as bacteria, E. coli and salmonella, affecting foods from fresh fruits and vegetables to meat and poultry.

It can also identify parasites in irrigation water as well as arsenic, cadmium, and lead in drinking water. "This small device can be used easily and quickly to check the safety of food at any stage in the food delivery or preparation process," said Stanciu.

Breaking Silos to Develop Innovative Bioelectronic Materials and Devices

Bioelectronics is expanding rapidly, driven by constant advances in semiconductor technology, chemistry, and the growing understandings of nano- and micro-biological systems. **Prof. Bryan Boudouris** (photo C), Professor of Chemical Engineering, and **Prof. Chi Hwan Lee** (photo D), Assistant Professor of Biomedical Engineering and Mechanical Engineering, realize that fulfilling the promise of bioelectronics requires research that crosses disciplines, so their labs are collaborating.

One revolutionary product under development by the team is a smart soft contact lens that measures eye pressure for glaucoma patients. Currently, there is no comfortable, non-invasive option for providing continuous measurement—especially while glaucoma patients sleep at home. This is concerning because a key cause of glaucoma—intraocular pressure (IOP) is at its peak during sleep.

The team's highly comfortable, day/night, sensored contact lens provides continuous tracking. The lens is being developed in collaboration with Dr. Pete Kollbaum, the Director of the Borish Center for Ophthalmic Research at the Indiana University School of Optometry. In addition, the device is being produced through a rapid prototyping process in a cost- and time-efficient manner, potentially allowing for future wide-spread distribution. Finally, telehealth is a priority. With the new, sensored lens, both glaucoma patients and their doctors will be able to receive e-updates about the status of their ocular health in real time.

"We are excited to continue to make key contributions to the bioelectronics ecosystem by bridging from computational chemistry and machine learning through materials synthesis and high-throughput manufacturing techniques such that true impacts are had in the clinic and in the lives of patients," said Boudouris.

Additional Research Team Members

FACULTY

Andres Arrieta: Asst. Prof. of Mechanical Engineering

Alex Chortos: Asst. Prof. of Mechanical Engineering

Jozef Kokini: Prof. of Food Science

Jacqueline Linnes: Asst. Prof. of Biomedical Engineering

Lisa Mauer: Director of Center for Food Safety Engineering, Prof. of Food Science

Saeed Mohammadi: Prof. of Electrical and Computer Engineering

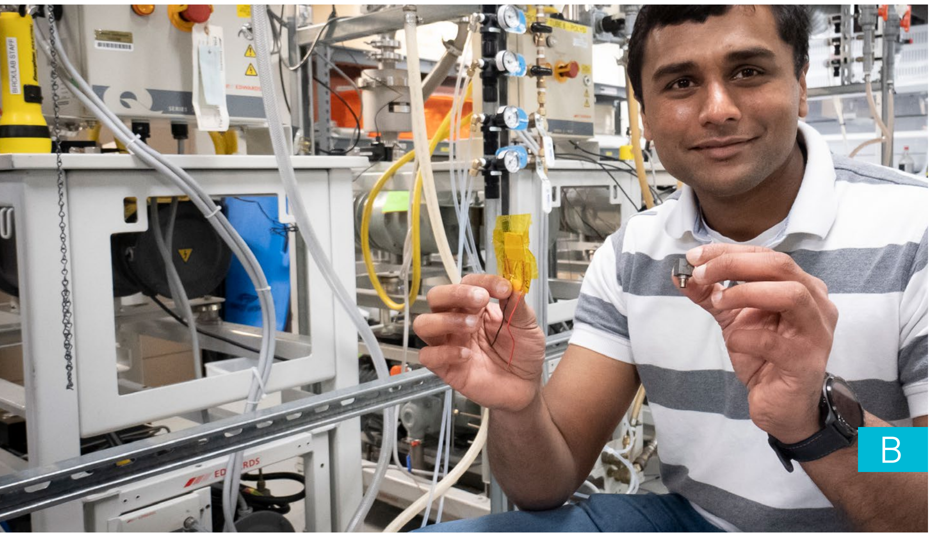
Kinam Park: Prof. of Pharmaceutics, Prof. of Biomedical Engineering

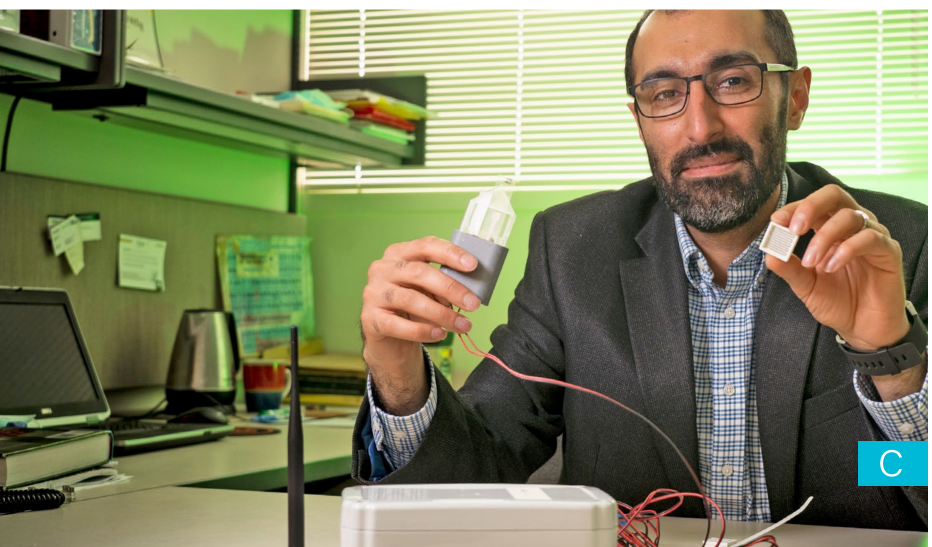
Dimitrios Peroulis: Head of the School of Electrical and Computer Engineering

Rodolfo Pinal: Assoc. Prof. of Industrial and Physical Pharmacy

Rahim Rahimi: Asst. Prof. of Materials Engineering

Babak Ziaie: Prof. of Electrical and Computer Engineering





Secure IoT Networking: Translating Data into Action

Sensors all around us are generating huge volumes of data. That data needs to be processed, analyzed, and if necessary, acted upon. All of this data is only useful if it leads to actionable insights.

Prof. Saurabh Bagchi (photo A), Professor of Electrical and Computer Engineering, is developing secure IoT networking platforms for both the manufacturing and agriculture sectors to enable this vision. Amazon AWS AI recently recognized the impact of his work with an Amazon Research Award.

For the manufacturing sector, large amounts of data are generated very quickly and potentially expensive decisions must be made based on this, such as: quickly readjusting the tool when production quality is low. This typically makes data analysis a significant challenge. Bagchi's team is streamlining this by providing a secure data analytics process directly within the network.

For the agriculture sector, Bagchi and his team are developing tools so data can travel over large areas at a low cost while also using very little energy. Bagchi's team uses long-range wireless protocol called LoRa for this. His solution ensures that data, such as soil quality and fertilizer content, can be collected securely and reliably over large networks in agricultural farms.

To translate each network's data into valuable insights, Bagchi's team consistently focuses upon two key priorities—data visualization and data security. Bagchi's team has developed easy-to-process, real-time visualization dashboards so complex data can become actionable information. Data security is also an imperative. Bagchi, working closely with Senior Research Scientists **Charilaos "Harris" Mousoulis** and **Nithin Raghunathan**, has developed a process that encrypts the data as quickly as it is generated to provide end-to-end security encryption.

"The data remains protected at every step of the process," said Bagchi.

Raw Data No More: Sensors that Provide Answers

Today's commercial preventative maintenance sensors provide useful but very raw data. Before manufacturers can actually answer the key question, "Is my equipment functioning well?," they must hire a data analyst to translate that raw data into information. This can be a costly and ongoing expense.

A team of Purdue faculty are striving to eliminate such costs by combining a preventative maintenance sensor with built-in machine learning and data analysis capabilities. Manufacturers will be able to quickly review their machines' health using one easy-to-understand dashboard. No dedicated staff analyst will be needed to examine raw data—saving time and money.

Furthermore, the Purdue researchers are rapidly scaling up their approach using transfer learning. Transfer learning uses one proven sensor as a starting point, allowing rapid progress when modeling a second sensor. Purdue's goal is to expedite the development of multiple, tailored sensors for a wide range of partners.

Saurabh Bagchi, Professor of Electrical and Computer Engineering; **John Sutherland**, Fehsenfeld Family Head of Environmental and Ecological Engineering; **Martin Byung-Guk Jun**, Associate Professor of Mechanical Engineering and Professor of Mechanical Engineering; and **Mukerrem Cakmak**, Reilly Professor of Materials Engineering and Mechanical Engineering are all working with Senior Research Scientists **Nithin Raghunathan** (photo B) and **Charilaos "Harris" Mousoulis** to develop these advanced sensors. Several companies—including Tate & Lyle, Fluke, and Evonik—are actively engaged as real-world testbeds. Through this multi-disciplinary approach in real-world manufacturing scenarios, the SMART Consortium is making rapid progress.

"Our goal is to lower the barrier to access for manufacturing companies," said Raghunathan. "We want this to be very affordable and easy to maintain. We are keeping those priorities in mind throughout every step of the way."

Scalability: Designing Healthcare and Agricultural Sensors for the Marketplace

For sensor innovation to successfully translate to the marketplace, it must also be scalable. **Prof. Rahim Rahimi** (photo C), Materials Engineering, has a key goal of innovating beyond sensors that address critical agriculture and healthcare needs. At the forefront of every new project, Rahimi ensures his team considers one key priority—scalability. "I do not want to simply develop one or two effective sensors in a lab," said Rahimi. "I want to be sure there is a path to produce millions of those sensors and do it affordably." Rahimi's team's current projects include:

- **Food Packaging:** Approximately 40% of food products go to waste. Currently, consumers rely upon an estimated date for freshness. Rahimi's team is using chipless, low-cost RFID tags to monitor moisture and oxygen inside a package—conveying the freshness of each product.
- **Fertilizer Assessments:** Fertilizer is a major expense for farmers, but there are few methods for optimizing its application. Rahimi's team is developing a module to be placed in a farm's nearest creekbed, as well as sensors throughout the farm. If there are high levels of nitrate or phosphate in the water, farmers know fertilizer is not being captured in the soil and adjust, saving money and improving water quality.
- **Soil Condition Applications:** Rahimi's team is developing batteryless RFID tags that have a microbial polymer with an adjustable rate of degradation. These very affordable, decomposable sensors can be scattered throughout the farm using a drone or robot, providing feedback about the soil's health. Rahimi's team is also developing low-cost, chipless electrochemical sensors that can be distributed throughout an agricultural field; an antennae can then interrogate the sensors to learn the soil's condition.
- **Wound Care:** Six million people in the U.S. are affected by wounds that do not heal properly. Rahimi's lab is developing a wound covering with low-cost sensors that can provide visible, quantitative assessments. A wound may be in the very stages of infection, for example, so the new bandage would change color and accelerate patient care. Sensored bandages can also be useful for telemedicine.

Additional Research Team Members

FACULTY

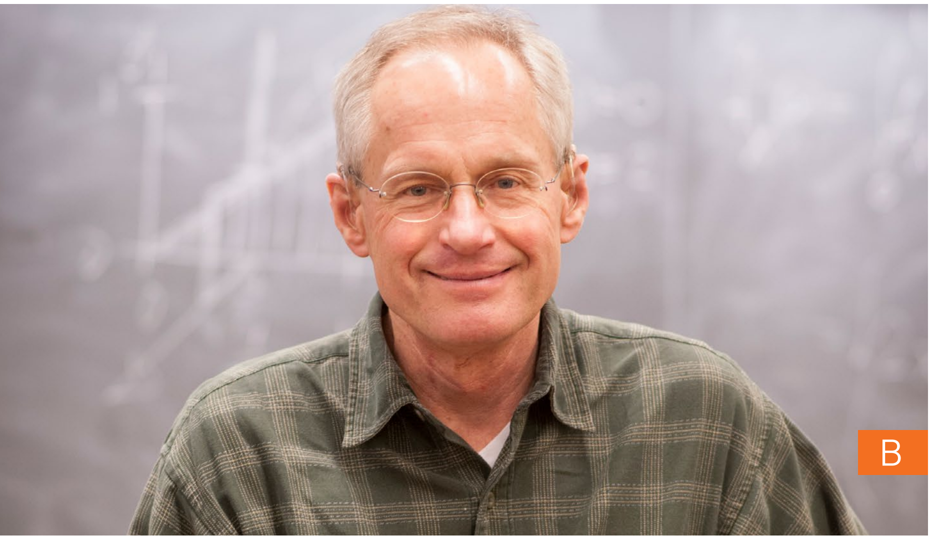
Jan-Anders Mansson: Distinguished Prof. of Materials Engineering and Chemical Engineering, Co-Director of IN-MaC

Dimitrios Peroulis: Head and Reilly Prof. of the School of Electrical and Computer Engineering

STAFF

Ted Fiock: WHIN-Purdue Managing Director


A


B


C

Theoretical / Computational Foundations of Modern Chemical and Biosensors

Prof. Muhammad (Ashraf) Alam (photo A), the Jai N. Gupta Professor of Electrical and Computer Engineering, has developed a theoretical and computational platform that allows his team to design and optimize sensors. Furthermore, Alam's deep understanding and use of data-analytics techniques allow his team to convert raw data obtained from sensors into actionable information.

The Alam Group focuses on creating the theoretical/computational foundation of modern chemical and biosensors so that one day in the near future these devices can be designed and integrated with the same precision as other more advanced electronic components, such as transistors, lasers, and photodetectors, and can be effortlessly integrated with modern integrated circuits and communication networks. Over the last 15 years, Alam has worked with a number of industrial partners on wearable and implantable biosensors for a variety of applications.

The Alam Group has developed the first theoretical model to interpret the steady-state and transient response of the nitrate electrochemical sensors, allowing them to interpret the field data with higher resolution than previously presumed possible. A novel physics-guided machine learning approach also allows the group to obtain reliable signals from unreliable sensors related to the inevitable degradation in the field. Digital ag companies can use the real-time sensor information from water runoff to decide optimum fertilizer levels or develop environmental policy decisions.

An additional project being pursued by the Alam Group is wearable electrochemical biosensors. Biofouling and statistical fluctuation in the sample volume in implantable/wearable sensors make it difficult to obtain a reliable measure of the analyte concentration because the characteristics of implantable sensors drift in unpredictable ways. Physics-based self-calibration techniques have been developed to obviate the challenge of biofouling in implantable/wearable sensors. This work will benefit the biomedical instrumentation companies as well as companies that integrate these sensors onto various mobile platforms for smart longer-lived implants.

Image-Based Quality Control: Producing Sensors Fast, Reliably

Prof. Jan Allebach (photo B), the Hewlett-Packard Distinguished Professor of Electrical and Computer Engineering, is proving an image can be worth far more than a thousand words. Through his work, manufacturers can develop a predictive model identifying how well a sensor will perform before it even leaves the roll-to-roll system—generating major cost savings.

Allebach is working to determine if a sensor's performance varies based upon an image of the ion selective membrane. To predict sensor performance, his team is using new applications of machine learning preprocessing methods. This involves conducting "trainings" to determine what information can be learned from existing sensors as well as "inferences" to predict what information can be gleaned in advance from new sensors.

Allebach envisions that, ultimately, the roll-to-roll system will identify and correct any sensor that does not fit the identified thickness parameters while they are being manufactured—saving significant time and money. The manufacturing system will also "learn" from the process, reducing the likelihood for future delays. Finally, the team will continually examine the sensors as they are used in the field, promoting further continuous quality improvement.

"Roll-to-roll manufacturing is an under-utilized technology," said Allebach. "It offers manufacturers affordable access to reliable and low-cost sensor technology."

Solving the Problem of Training Data Scarcity and Privacy for Machine Learning

Today, there are plenty of sophisticated machine learning techniques that allow one to learn patterns from datasets. These patterns can be used for many important applications—such as inventory predictions, classifying information, and making consumer recommendations.

However, a major problem organizations face in the use of machine learning is the scarcity of training datasets. Often, obtaining training datasets is an expensive, time-intensive process.

Prof. Elisa Bertino (photo C), the Samuel D. Conte Professor of Computer Science, and her collaborators are developing transfer learning techniques to address such problems. Through transfer learning, a machine learning model can be trained for use in different domains—which reduces costs and saves time. As always with machine learning techniques, not every technique works for every type of data. So, Bertino and her collaborators have designed and experimentally evaluated its techniques for two different application domains:

- **Identification of Civil Infrastructure Failures from Images:** Bertino and collaborators used two publicly available deep neural networks, trained to recognize objects from images, and adapted them for identifying cracks and corrosions from images. Even though those publicly available networks had not been trained to recognize those failures, the adaptation approach reduced the amount of training data needed by 50%.
- **Computer Network Security:** The team's goal is to build a deep neural network able to identify malicious network packets. In this case, the data are records containing numeric and categorical data. Also, in this case, results show that transferring a network trained in one domain to another substantially reduces the amount of training data required in the second domain.

As someone interested in applying machine learning to real-world problems, Bertino's lab is focusing also on ensuring that transfer learning techniques do not undermine privacy and data confidentiality and that machine learning models are trustworthy. This is a synergistic combination that is vital for long-term robust solutions. However, adequate solutions are often domain specific. Designing them requires tight collaborations between academic research teams and industry. By working together, corporate collaborations provide high-quality insights to both research teams and industrial organizations.

Additional Research Team Members

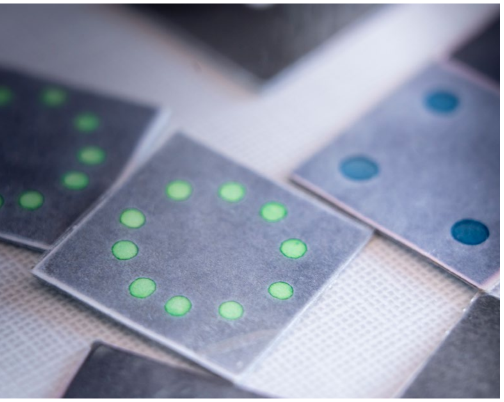
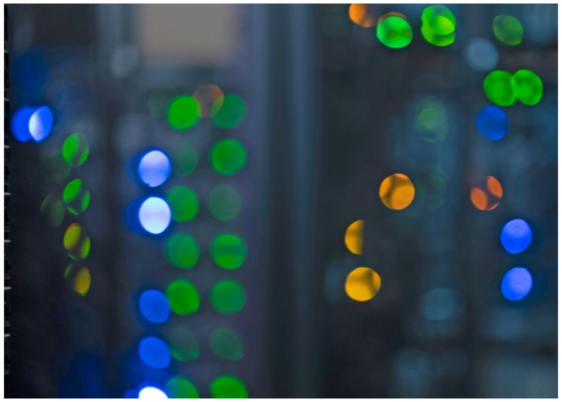
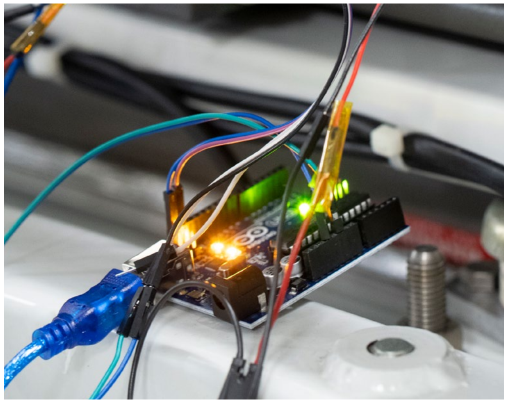
FACULTY:

Saurabh Bagchi: Prof. of Electrical and Computer Engineering and Prof. of Computer Science

Mohammad Reza Jahanshah: Assoc. Prof. of Civil Engineering

Bruno Ribeiro: Asst. Prof. of Computer Science

Shreyas Sen: Elmore Associate Prof. of Electrical and Computer Engineering


Thank You!

The Purdue University SMART Films Consortium appreciates your interest and time reviewing our work. If you have any questions about our team's research or are interested in becoming a Consortium member, please send an email to: shakouri@purdue.edu.