Mobile sensors
Autonomous exploration in a dynamic environment

The tsunami that struck Japan on March 11, 2011. Missing Malaysia Airlines flight MH37. Both show the critical need for robots capable of working together as a mobile sensor network in a highly dynamic, potentially hazardous environment.

Nina Mahmoudian wants to increase the effectiveness of the response by robots to environmental and human disasters. Her goal: to develop tools and algorithms that lower deployment and operating costs, increase efficiency and boost endurance for missions with a high level of complexity, including coastal surveillance, subsea structural inspection, hazards detection, and rescue and relief.

“What is really needed for search missions that require vast underwater inspection and detection, such as locating boats and aircrafts at sea, is an underwater robot that can explore an area with a sense of what it is looking for,” says Mahmoudian. Even better: A fleet of underwater robots. “In contrast to the use of a single vehicle, multi-robot systems could vastly increase mission area, decrease operation time, and offer a diverse suite of sensors, system resiliency, and goal redundancy,” she adds.

Mahmoudian and her research team at the Michigan Tech Nonlinear and Autonomous System Laboratory are building four such robots: low-cost autonomous underwater vehicles (AUVs), each weighing about twenty-five pounds. Named ROUGHIE (for Research Oriented Underwater Glider for Hands-On Investigative Engineering) Mahmoudian’s AUVs sport better, more powerful brains equipped with multi-agent motion control algorithms and tools for more efficient underwater discovery. They are also modular, allowing users to swap out different components depending on what tasks the AUVs undertake.

Powered only by batteries, ROUGHIEs “fly” slowly through the water simply by adjusting their buoyancy and weight. “They are designed for use near the water’s edge, which offers a special challenge,” adds Mahmoudian. “ROUGHIEs will come up on the coast, which means they have to operate where there’s lots of traffic and noise.”

ROUGHIEs are also less expensive than commercial gliders. “At a fraction of the cost of one commercial vehicle, it is possible for us to test glider swarm algorithms and compare them to established single glider models,” she says. “Testing control methods for hazardous underwater zones such as ports, shipping channels, and reefs can be done without much financial risk.”

Mahmoudian’s work combines fundamental and applied research. “One of our goals is to facilitate a seamless transition between academic modeling/simulation problem-solving approaches and real-world applications.”

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Since 2008, explosive hazard attacks in Afghanistan have wounded or killed nearly 10,000 US soldiers. Worldwide, explosive hazards, on average, cause 310 deaths and 833 injuries per month. Timothy Havens aims to reduce these numbers by developing methods to find these hazards by combining information from multiple types of sensors, including ground-penetrating radars and cameras.

Havens investigates signal processing and machine learning, focusing on computational intelligence (sometimes called artificial intelligence) algorithms that can perform tasks autonomously. His research team develops algorithms that automatically detect and locate explosive hazards using two different systems: a vehicle-mounted multi-band ground-penetrating radar system and a handheld multi-modal sensor system.

“Each of these systems employs multiple sensors, including different frequencies of ground-penetrating radar, magnetometers and visible-spectrum cameras. We are creating methods that integrate the sensor information in order to automatically find the explosive hazards. Our imaging and detection methods provide a 150% improvement in a standard area-under-ROC (receiver operating characteristic) analysis,” he adds.

“Recently, the Army has begun testing a forward-looking system that combines L-band and X-band radar arrays. Our team is also focused on developing imaging and detection methods for this sensor-fused system," he explains.

In another project, Havens is collaborating with other researchers from Michigan Tech and the Michigan Tech Research Institute (MTRI) to create a sensor-fused platform for inspecting transportation infrastructure, such as roadways and bridges, from an unmanned aerial vehicle (UAV). His research team has developed a UAV sensor pod that combines information from Light Detection and Ranging (LIDAR), camera, and inertial sensors to measure three-dimensional information about road and bridge surfaces. “This project will revolutionize how transportation inspection is performed, both speeding up the process and also significantly improving the safety of transportation workers,” he says.
Maintaining a world-class transportation infrastructure—highway, railway, and pipeline—is critical for the health of the US economy. Geotechnical assets are literally the foundation. These geotechnical assets include embankments, cut slopes, tunnels, foundations, retaining walls, and more.

Current management practices for geotechnical assets along the transportation corridor often involve restoring the asset after any failure rather than identifying and remediating hazardous conditions before they occur. Since such assets are vast, and the cost and labor for manual monitoring are prohibitive, transportation agencies are not engaged in proactive monitoring. Thomas Oommen believes that remote sensing from satellite, aerial, or mobile platforms using Radio Detection and Ranging (RADAR), Light Detection and Ranging (LIDAR), or optical sensors could provide an economically-sustainable proactive solution. “Such sensors are not only capable of imaging the asset, but they also can be used to quantify precise measurements of movements in mm to cm scale over time,” Oommen explains. “The challenge involves relating these movement measurements to the condition of the asset in a meaningful way, and identifying which platform and sensor are most useful for different geotechnical assets in varying transportation environments—highway, railway, and pipelines.”

Oommen and his research team are attempting to address these challenges by imaging various geotechnical assets in different transportation environments. They are employing different sensors and platforms and relating their conditions to a remotely-sensed image. The team is also conducting lab-scale studies to understand the limitations of the various sensors.

“Aging infrastructure, changing weather patterns with more precipitation, and increased volumes of heavier and faster traffic have all placed a great burden on geotechnical assets along the transportation corridor,” adds Oommen. “Proactive monitoring is extremely important for strategic long-term investments and hazard prevention.”

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Our research DEFINES INNOVATION

Copper interconnect, meet carbon nanotube
Creating faster circuits

As technology scales beyond 16-nanometer technology node, the performance of copper interconnects in circuits is approaching its fundamental physical limit.

Timing and reliability issues that perplex copper interconnects limit circuit miniaturization.

Wires made from copper have very small cross-sectional areas. This results in increased wire resistance and excessive interconnect delay. In fact, interconnect delay has become the limiting factor for chip timing.

Due to the fundamental physical limits of copper wires, novel on-chip interconnect materials—carbon nanotubes and graphene nanoribbons—are more desirable due to their many salient features including superior electrical conductivity, increased electromigration, high thermal conductivity, and mechanical strength.

Shiyan Hu seeks to bring together the benefits of both copper interconnects and carbon nanotubes and/or graphene nanoribbons.

With a $430,000 Faculty Early Career Development (CAREER) Award from the National Science Foundation, Hu will develop an innovative codesign methodology for next-generation integrated circuits (ICs).

The wires in a typical computer chip are very narrow indeed: with a width of about 22 nanometers, each bundle of a thousand is no bigger than a human hair.

"Those wires have been getting thinner and thinner, because people want their chips to do more and more things, and for that you need more and more transistors, billions on a single chip," Hu explains. "But then the chip gets slower and slower ... unless you do some magic."

Hu will develop a variety of physical design automation techniques. A key feature will be a "variation-aware" codesign technique for the new methodology to compensate for variation and defects.

"The replacement of copper interconnects should be performed gradually in order to judiciously integrate the benefits of both technologies," adds Hu.

"My goal is to integrate pioneering nanotechnologies into practical circuit design," Hu explains. "I think we can revolutionize the prevailing circuit design paradigm."

Hu's other research interests include embedded system designs for smart homes, microfluidic biochip design, and buffer insertion, which greatly improves integrated circuits' timing performance.

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Electric power has been a key factor in creating a healthy and comfortable society. Unfortunately, conventional sources are plagued with unacceptable liabilities. Solar photovoltaic (PV) technology, which converts sunlight directly into clean and green electricity, is poised to replace those sources—and this is the goal of a team of undergraduates, graduate students and post-docs working with Joshua Pearce on every aspect of PV technology, including the fundamental materials science, device physics, solar electrical system design and energy policy.

The US solar industry is growing at a record-breaking pace, while becoming more affordable and accessible than ever before. In many parts of the country, solar electricity is already cost-competitive with traditional energy sources. The average price for a utility-scale PV project dropped from about $0.21 per kilowatt-hour in 2010 to $0.11 per kilowatt-hour at the end of 2013. According to the Energy Information Administration, the average US electricity price is about $0.12 per kilowatt-hour, and can run higher than $0.20 per kilowatt-hour in Michigan’s Upper Peninsula, New York, and elsewhere.

Although solar power costs have plummeted, most American families still simply do not have enough cash to purchase a PV system to meet their needs; they need a loan with reasonable terms. Securitization, or a pooling of solar assets for investors, provides a solution to this problem as shown in a study by Pearce’s research group that found billions of dollars of potential solar asset-backed securities in the US. “With the current cost of solar equipment and our financing model the home owners make money, the solar industry makes money and the firms setting up the financing make money. There is no question, the solar industry is ready for investors,” says Pearce.

His group is working to reduce costs on several other fronts. Last year, the group investigated spectral effects of albedo (reflection) from surfaces around PV systems and found that by using non-tracking planar concentrators (small mirrors) they could increase PV output by more than 30 percent. “Firms avoid using such mirrors now because of fear of voiding warranties,” says Pearce. “Our work is starting to provide the data needed to lessen these fears, and we are developing optical models for non-ideal surfaces to optimize PV systems for the real world.”

In addition, Pearce’s group found they could increase efficiency by using the PV module as a heat absorber for solar thermal applications. “The trick is to be careful about PV material choice and use the thermal system to anneal (bake) the PV to refresh it,” he adds. Their results pumped up the electrical output by another 10 percent. “Our work enables PV systems to be optimized for a specific location, which drives the cost of solar even lower,” Pearce concludes. “Soon most roof tops will sport a solar power system for economic reasons alone.”

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Our research IMPROVES LIVES

Sure-footed
Improving mobility and agility in amputees

Mo Rastgaar is developing a lightweight, cable-driven, powered ankle-foot prosthesis capable of steering and even traversing slopes. He has received a National Science Foundation grant of nearly $500,000 to make his new artificial-limb design a reality. With this five-year Faculty Early Career Development (CAREER) Award, Rastgaar will further develop his powered ankle-foot prosthesis. His goal: to create an artificial lower leg with the unique ability to restore amputees’ mobility and agility.

To do this, Rastgaar will develop an ankle joint with two controllable degrees of freedom. His research is based on exploring the turning mechanisms in humans, and understanding the contribution of the ankle and steering mechanisms in human gait. Rastgaar’s team of graduate and undergraduate students at the Human-Interactive Robotics Lab (HiRoLab) have developed a prototype of a powered, steerable ankle-foot prosthesis as well as the infrastructure for evaluating this novel prosthetic robot, which features different sensors to detect how an amputee is walking and incorporate real-time force and trajectory feedback control. As the person walks, signals are sent to a microprocessor that adjusts the prosthesis to match the gait of the individual. The additional degrees of freedom provided in this innovative ankle-foot prosthesis will not only improve the gait of amputees as they stride across undulating terrain, but also reduce the likelihood of falling.

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An alternative to risky surgery, thermal ablation is used to treat tumors in the liver, kidneys, and lungs. Thermal ablation uses very high temperatures to destroy a small area of cells. The high heat kills cancer cells by coagulating their proteins and destroying nearby blood vessels—in effect “cooking” them.

Radio-frequency waves, microwaves, ultrasound waves, and other forms of energy can be used to heat the area. Heat can be applied by insertion of a small applicator (such as a needle or a microwave antenna) into a cancer or by focusing acoustic/laser energy on a tumor in a touchless fashion.

Early results are promising, but thermal ablation has its challenges. Failure to ablate the entire tumor, which is particularly difficult at the edges, can result in regrowth of the residual tumor. In radiofrequency ablation (RFA), using too much heat can destroy healthy surrounding tissues. For instance, renal tissues could be accidentally damaged during a liver ablation procedure conducted without effective image monitoring.

Jingfeng Jiang is developing ultrasound-based image guidance algorithms for thermal ablation to ensure a complete denaturation while sparing surrounding tissue. Jiang’s Biocomplexity and Mechanics Lab at Michigan Tech is partnering with an interdisciplinary team at the University of Wisconsin–Madison to investigate real-time ultrasonic monitoring of thermal ablation therapy. Jiang’s novel computer algorithms will monitor the tissue stiffness changes associated with thermal ablation, and these algorithms will be used for (Phase I) clinical trials in human patients at the University of Wisconsin Hospitals and Comprehensive Cancer Center.

Jiang uses ultrasound-based elastic modulus imaging (EMI) to better view thermal ablation zones. “Elastic modulus is a physics term for hardness. The elastic modulus image represents spatial (hardness) distributions of the tissue. EMI is created based on ultrasound-based measurements such as displacements. After all, the stiffer spring deforms less. Ablated tissue is stiffer,” he explains.

“Our goal is to help surgeons gain better control during the procedure. It can be difficult to accurately measure the temperature inside a tumor. Nearby tissues can be negatively affected. By monitoring temperature and tissue stiffness during treatment and adjusting heat levels accordingly, thermal ablation can be more precise and offer patients better results. The initial answer is yes. Surgeons like what they see so far.”

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Frost-resistant concrete

Damage, diagnosis and simulation

The durability of concrete plays a central role in the sustainability of the US infrastructure system, with broad economic, social and environmental impacts. Internal frost damage is one of the major problems affecting the durability of concrete in cold regions.

Qingli Dai has developed microstructure-based models to describe the effects of freeze-thaw cycles on the durability of concrete—computational tools that can prevent excessive internal frost damage through improved mix design and construction control. Her research includes the fabrication, analysis and testing of multifunctional structural materials, and the fusion of sensor detection and computational modeling to better understand damage mechanisms.

"Crystallization pressure due to ice nucleation within capillary pores is the primary cause of internal-frost damage of concrete," Dai explains. “When pressure is greater than the strength of the concrete, damage occurs." Dai has examined the multi-physical processes from basic fundamental thermodynamic principles to determine the magnitude of the ice crystallization pressure on the pore wall. She supplements her analyses with input parameters such as pore microstructure, temperature and free water content of the specimen.

Dai has also developed a unique time domain reflectometry sensor to monitor the amount of free water in concrete and the crystallization process in real time. Dai characterizes nanoscale or micronscale pore microstructure with Transmission X-ray Tomography (TXM) images.

Using two idealized pore systems based on these images, Dai simulated the damage processes that occur due to ice crystallization. Then, she calculated crystallization pressure in capillary pores with thermodynamic analysis at different subcooling temperatures. Dai found that crystallization pressure can significantly increase to cause internal damage when the subcooling temperature is reduced only a few degrees.

“I believe this research method, which integrates microstructure characterization and sensor detection, will reveal other damage mechanisms of infrastructure materials in nano- or micro-scales.”

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Our research CREATES THE FUTURE

Infectious diseases
Binding peptides to pathogens for detection and removal

Millions of people die every year from infectious diseases. Illness such as AIDS or West Nile are caused by viruses. Bacteria, such as cholera or salmonella, can also be deadly. The incident of disease transmission, be it through contaminated water or food, touching a contaminated surface, or through a blood transfusion, could be reduced by the creation of specific and custom-tailored removal and detection devices.

Caryn Heldt is examining methods to bind peptides to pathogens. Her goal: To discover a better sensory element—an alternative to antibodies—that can be applied in a more economical device.

“Peptides are small pieces of proteins, like antibodies, but due to their small size, are more stable,” she explains. The peptides under investigation are composed of the same twenty different naturally occurring amino acids as antibodies, giving them a similar diversity as antibodies to bind using multiple functional groups. Heldt and her team are not only interested in discovering new sensor peptide elements, but also hope to use these sensory elements in unique devices to remove and detect pathogens in a manner that is economical and environmentally sustainable.

Many such devices today are based on specific antibodies that bind to pathogens for detection or removal,” she notes. Pitfalls for such devices include a short shelf life, required refrigeration, and/or specialized laboratory equipment to analyze results.

Heldt is currently using porcine parvovirus as a model virus to test the removal and detection ability of different devices. Small peptides are being added to different membrane surfaces to create a virus filter that could purify water without the need for high pressure pumping—something that could potentially reduce the cost of producing clean water for personal use or for larger populations.

The team is also investigating the use of peptides as a specific sensor surface to create a low power device that can detect a virus in minutes instead of hours or days, reducing clinical delays. Other virus removal techniques are being pursued for more specialized applications, as well, such as the removal of viruses from biotherapeutics, including virus precipitation and extraction.

“All of these methods rely on the specific binding of small peptides to detect or remove viruses,” adds Heldt. “These sensory elements could also be discovered for different pathogens and used to remove pathogens from the environment. We hope to reduce the number of deaths that are caused every year by infectious diseases.”

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