SIGNATURES

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Engineering Advances at the University of Notre Dame

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Although not a new concept, network embedded systems are being used in novel ways in a variety of research initiatives. From civil structures and defense systems to environmental and health monitoring, networked embedded systems represent the next generation in computing, communications, and technologies, where individual sensors react to, communicate with, organize, and maintain themselves in relationship to each other, to the entire system, and to the environment in which the system is placed.

the winds of change

The American poet James Russell Lowell once said, "There is no good arguing with the inevitable. The only argument available with an east wind is to put on your overcoat." Change is inevitable, but it can also be exciting. One of the most exciting changes occurring today is the proliferation of embedded systems and the development of large-scale distributed systems which include real-time routing, independent data collection, and autonomous behavior.

"There are two very important notions about embedded systems," says **Panos J. Antsaklis,** the H.C. and E.A. Brosey Professor of Electrical Engineering. "Most obvious is the fact that they are embedded. You cannot access an embedded system and change its programming as easily as you could that of a computer. As important is that the mission of these little computers – because that's what a microprocessor is, and embedded systems are made up of microprocessors – is not to 'compute.' It is to improve the function of the device in which it is embedded."

Perhaps the most widely publicized embedded system in consumer products today is the OnStar® service, which is available in a variety of new cars, trucks, and recreational vehicles. OnStar tracks vehicles and assists drivers as needed in real time, providing services such as air bag deployment notification, roadside assistance, stolen vehicle tracking, remote door unlock, and remote diagnostics. But it is just one example of an embedded system.

Embedded systems are prevalent in households around the world. Washing machines, dryers, microwaves, and cell phones all feature embedded systems. They were developed by engineers who embraced the change that has been steadily progressing since Jack Kilby and Robert Noyce first introduced the microchip in the early 1960s. In essence OnStar and other embedded systems take a microprocessor, originally used to analyze data or interact with a desktop user according to a series of commands, and instead program it to interact with the real world. The benefits of using embedded systems in consumer products are obvious; they raise the quality of life by making products more functional and more efficient.

Equally as positive are the benefits derived when embedded systems technology is applied to a variety of research projects, such as the work being accomplished at the University of Notre Dame. Following Lowell's analogy, faculty in the College of Engineering are not "putting on their overcoats" in an effort to shield themselves from the change but to embrace it. Donning their boots and hats and running headlong into the "east wind," they are leading the way in developing network embedded systems for research in disciplines not previously employing this type of sophisticated technology.

Tracy Kijewski-Correa, the Rooney Family Assistant Professor of Civil Engineering and Geological Sciences, monitors the static and dynamic performance of several tall buildings in downtown Chicago from Notre Dame's NatHaz Modeling Laboratory. Using the Leica MC500 Global Positioning System (GPS) with Real Time Kinematic potential, Kijewski-Correa and Ahsan Kareem, the Robert Moran Professor of Civil Engineering and Geological Sciences — in collaboration with researchers from Skidmore, Owings & Merrill LLP, and the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario — are able to track the movement of these structures down to five millimeters with data acquired at one-tenth of a second, instead of one minute, intervals. In addition to monitoring the tall buildings, Kijewski-Correa and Kareem utilize a low-rise base station in Chicago to enhance the accuracy of the GPS. The project is funded by the National Science Foundation.

For example, as part of a National Science Foundation study, **Ahsan Kareem,** the Robert Moran Professor of Civil Engineering and Geological Sciences, and Rooney Family Assistant Professor **Tracy Kijewski-Correa** are using networked embedded devices to monitor the structural performance of several tall buildings in Chicago. They are working with Skidmore, Owings & Merrill LLP (SOM), one of the world's premier architecture and engineering firms and the company responsible for the design of structures such as the Sears Tower, the Lever House in New York City, and the Bank of America World Headquarters in San Francisco. Another partner in the study is the Boundary Layer Wind Tunnel Laboratory of the University of Western Ontario, a world leader in commercial wind tunnel testing.

"We've been interested in how wind affects the performance of tall buildings for several years," says Kareem. "This particular study focuses on some of the signature structures in the world, which were designed and built at a time when scale-model testing and computer modeling were not as advanced as they are today. We want to determine if the structures are behaving in the manner for which they were designed."

Questions Kareem and the research team, known as Team Chicago, are asking include: Were the procedures used at the time of the structures' design representative of realistic loadings and response? Are the structures performing as expected? And, if they are not, how does that impact design criteria for the next generation of urban structures?

Hour by hour the sun and the rain, the air and the rust, and the press of time running into centuries, play on the building inside and out and use it.

— Carl Sandburg, *Skyscraper*

Modeling technologies have changed over the years, but cityscapes have also changed. The urban landscape of Chicago, for instance, is much more developed than it was a few decades ago, when buildings like the Sears Tower and the Aon (Amoco) Building were designed. Thus, the wind travels through cities and buffets buildings in a much different manner than it did in the early 1970s.

Kareem and Kijewski-Correa are using traditional monitoring devices, such as anemometers and accelerometers, in conjunction with cutting-edge technology such as the Leica MC500 Global Positioning System (GPS) with Real Time Kinematic potential. Four accelerometers have been mounted in pairs in opposite corners on the highest floor of each building in the study. This positioning enables detection of a building's motion along its two lateral perpendicular axes, as well as twisting movements.

"We use high-precision servo-force balance accelerometers," says Kijewski-Correa, "because these buildings move at very low amplitudes and with long periods. It's not like measuring a seismic event, where you see much larger levels of motion."

According to Kareem, stand-alone implementation of this technology does not provide sufficient accuracy to monitor building displacements as indicators of performance. In order to make corrections for atmospheric conditions that affect the GPS signal, he and Kijewski-Correa use a low-rise structure in the city as a base station. This differential monitoring reduces errors to as little as five millimeters. Using this measurement protocol, the Notre Dame team can monitor a building's movements every one-tenth of a second. (A real-time feed of the data can also be used by owners in the daily management of the buildings in the study, including the operation of elevator systems and skydecks.)

"What's important to remember is that even before

High-precision Columbia sensors are placed in pairs in opposite corners of the top floor of each building in the study. This allows researchers to detect the motions of the structures along lateral perpendicular axes, as well as twisting motions. An ultrasonic anemometer and Global Positioning System antenna, shown above, are also utilized in the study. Before installing any hardware, however, the Notre Dame team spent two years calibrating the sensors to the urban environment in order to assure reliable measurements.

Embedded: It's a way of life.

When Jack Kilby and Robert Noyce first introduced the microchip in the early 1960s, they drastically changed the course of the computer industry by transforming room-sized machines into an array of mainframes, mini, and personal computers. Their chip was used to make computers. But it touched many other industries as well: education, transportation, manufacturing, and entertainment. In fact, the impact of the microprocessor on the life of the average person has been likened to the changes wrought by the Industrial Revolution.

Today, microprocessors are literally everywhere. And the number of chips being manufactured to meet an ever-growing consumer demand is enormous. More than a quarter of a billion microprocessors are built and sold every month.

But they are not manufactured for traditional computer applications. Instead, these chips are embedded in products such as washing machines, dryers, dishwashers, refrigerators, televisions, stereos, automatic garage door openers, microwaves, and cell phones. In fact, it's difficult to name an electronic or electro-mechanical device in a home today that does not feature one or more embedded microprocessors.

There are approximately 50 microprocessors in an average middle-class American household today. Add a personal computer and that number jumps to 60. Add a car, depending on the model, and the number of microprocessors in a typical household doubles. In fact, on any given day, an individual might interact with as many as 70 microprocessors before lunch.

While microprocessors are found in household products, they are also present in children's games, toys, and a variety of other devices. The recently introduced Segway, a self-balancing people mover, contains 10 microprocessors. The Mercedes C-Class sedan features 153 microprocessors and offers an optional satellite-based communication system, stock updates, and emergency assistance.

The most exciting thing about microprocessors is that there is no such thing as a "typical" embedded system. But they all have one thing in common: Embedded processors are being used by a variety of industries and researchers in a number of different ways to help improve the way people live.

The Adaptive-optic Challenge

Aero-optics is the study of the interaction of light with a turbulent flow. The light could emanate from distant space objects or celestial bodies, or it could be a laser beam. In general, the interaction of these optical signals with turbulent air has a degrading effect, which is why stars appear to twinkle. This effect is particularly devastating to the quality of a laser beam projected from an aircraft, where the thin layer of turbulent air surrounding an aircraft can reduce the focus of a laser on a distant target to less than 1 percent of its intensity.

Airborne imaging faces a similar challenge; for example, an airborne camera might be able to image a vehicle from 60,000 ft. with sufficient resolution to identify it as a car, but it may not be able to read the license plate. Using high-speed wavefront sensors developed at Notre Dame; multiple dedicated, embedded processors; deformable mirror technology; and the Notre Dame Shear-Layer Facility, a team of researchers led by **Eric J. Jumper,** professor of aerospace and mechanical engineering, is preparing to measure the distortion of the laser beam, develop the conjugate of the distortion, adjust a deformable mirror – which will be part of the embedded system, and restore the laser beam's quality by bending the mirror up to 15,000 times per second. In short, the team is developing the technology that will allow an aircraft flying at high Mach numbers to project correctly configured laser beams, a feat thought impossible only a few years ago. "This is a very dynamic process," says Jumper, "so a traditional approach to an adaptive-optic correction was not feasible. We have incorporated flow control, high-frequency non-real-time wavefront sensing, and a new approach to controlling adaptive optics into making this correction. We could not have achieved our successes to date without embedded, dedicated processors. There are too many calculations that need to be made in order to determine the mirror's configuration and compensate for the wavefront aberration efficiently and effectively."

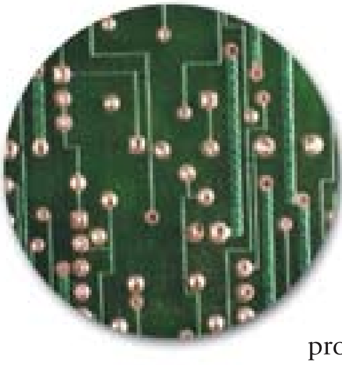
The above circuit board, developed at Notre Dame by Professor Eric J. Jumper and designed by Joel Preston, an electronic specialist in the Department of Aerospace and Mechanical Engineering, features 64 amplifiers, supporting a 4 x 4 sensor array. Four of these arrays will be ganged to form an 8 x 8 array. UDT Corporation is making the sensors, which will line up with the actuators on a deformable mirror, built by Xenetics Corporation. Jumper's research is funded through a contract with Oceanit, a Hawaii-based engineering, science, and research company under the sponsorship of the Air Force Office of Scientific Research. He is also working with the Air Force Research Laboratory, Boeing, and Northrop Grumman.

we installed the hardware and began collecting data, we spent two years calibrating the equipment in relation to the GPS system," says Kareem. "Because of this, we are very confident in our data."

Information from the sensors is transmitted to a communications hub in the SOM building in Chicago and then relayed, via the Ethernet, to Notre Dame, where it is archived in a web-assisted database and analyzed. Scale models of the structures and the surrounding built environment are then developed in the Boundary Layer Wind Tunnel to compare the predicted response to full-scale data.

"In essence we're tracking the vital signs of individual structures in order to give us a better indication of in-situ building performance," says Kijewski-Correa. "By using conventional and advanced sensors, Notre Dame is taking the lead in the integrated monitoring of tall structures. We are not designing the sensors themselves, but we have adapted and prototyped a networked configuration of these devices for capturing signals peculiar to long-period civil structures. Our findings could directly impact the architectural and structural communities for years to come."

According to **Martin Haenggi,** assistant professor of electrical engineering, networked embedded systems can also be placed in natural

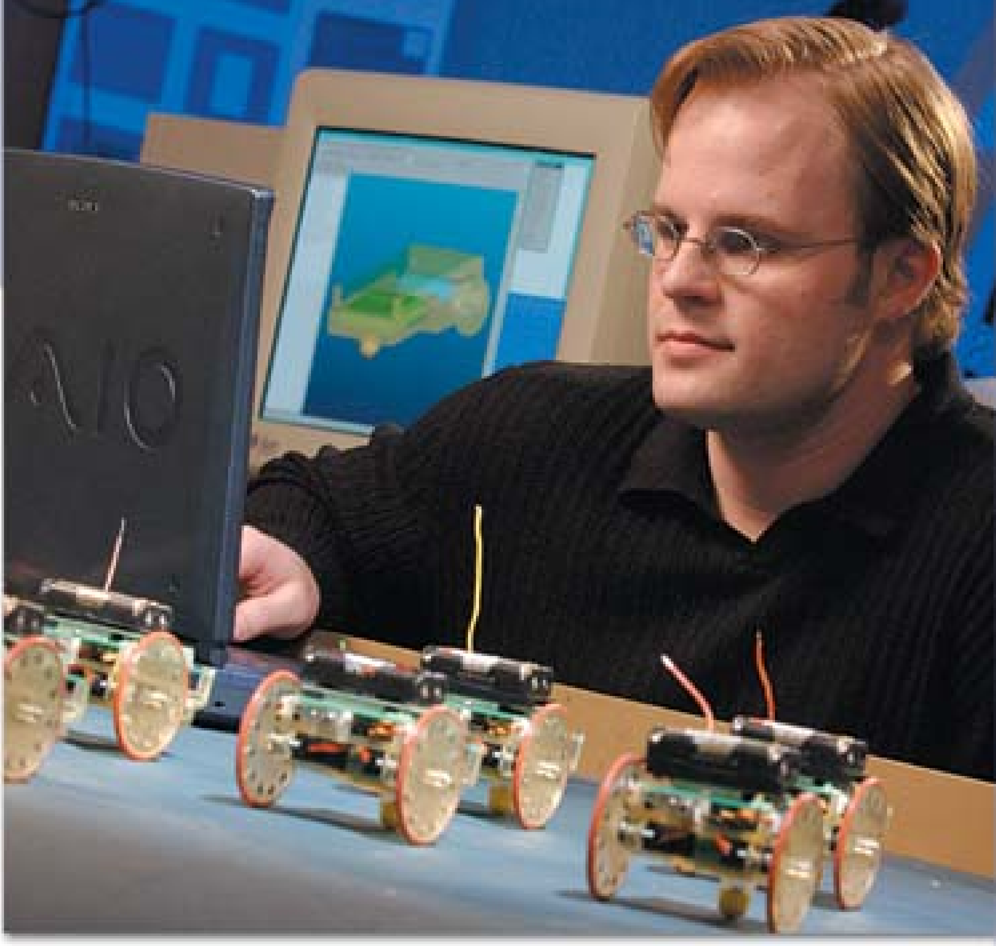


environments, enabling researchers to observe any kind of habitat at the scale and in the amount of detail that has never before been possible. Haenggi and a team of researchers from throughout the College of Engineering are developing an embedded sensor network for monitoring the hydrology and ecology of freshwater lakes and streams, the Naiades project.

Named for the nymphs of rivers, lakes, and streams of Greek mythology, Naiades represents what will be a five-year collaborative effort between researchers in the Department of Electrical Engineering and the University's Center for Environmental Science and Technology (CEST), including team leaders **Patricia A. Maurice,** professor of civil engineering and geological sciences and director of CEST, and **Michael D. Lemmon,** associate professor of electrical engineering. Other faculty currently involved in the project are Antsaklis; Haenggi; **Sharon Hu,** associate professor of computer science and engineering; **J. Nicholas Laneman,** assistant professor of electrical engineering, **Agnes E. Ostafin,** assistant professor of chemical and biomolecular engineering; **Jeffrey W. Talley,** assistant professor of civil engineering and geological sciences; and George Hornberger, the Ernest H. Ern Professor of Environmental Sciences at the University of Virginia.

"The Naiades project," says Maurice, "has the potential of greatly enhancing our knowledge of the hydrologic cycle, water quality, pollution, the potential effects of microorganisms, and even biological warfare. It's an innovative solution to building better environmental models so we can better understand our world and what impacts it."

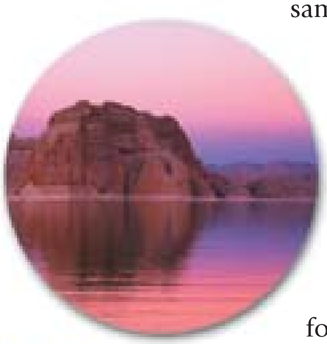
According to J. Nicholas Laneman, assistant professor of electrical engineering, one of the unique aspects of the University's research in networked embedded systems is the test bed located in the Department of Electrical Engineering. The test bed — developed by H.C. and E.A. Brosey Professor Panos J. Antsaklis, Associate Professor Michael D. Lemmon, and Assistant Professor Martin Haenggi as part of the Network Embedded Software Technology project and funded by the Defense Advanced Research Projects Agency — is one of a handful of such facilities in the country. It allows researchers and students, like doctoral candidate Qiang Ling, shown here, to build and validate their networks in order to help determine the best ways to develop hardware and software, as well as ways to improve network communication and node performance while operating on limited power. The new protocols developed as a result of this type of research may eventually be used for the long-term autonomous monitoring of a variety of systems, from large-scale manufacturing applications and social networks to monitoring the habitats of endangered species.



Brett McMickell, above, a graduate student in the Department of Aerospace and Mechanical Engineering, and Assistant Professor J. William Goodwine have designed and built prototypes of mobile robots (motes), using the same University of California-Berkeley microprocessor employed by the Naiades team, and an experimental hardware platform that focuses on maintaining a robust and reliable ad hoc network. Each of the motes McMickell and Goodwine have built communicates through radio frequencies to identify where its neighbors are and to maintain a specific formation when mobile. Goodwine's work in control theory is funded by the National Science Foundation.

Current technology dictates that a researcher seeking to understand the physicochemical reactions that occur in a lake or stream has to either collect samples — physically go to the lake or stream, gather water, and take it back to a lab for testing — or set up a commercial sensor in the water to record variables in things like pH or conductivity. The trouble has been that the real world involves a variety of spatial and temporal scales not addressed by these testing methods. Although researchers gather samples under a variety of conditions, they do not normally collect data during sub-zero temperatures or thunderstorms. In addition, even the most accurate commercial sensors have been limited in the number of samples or amount of information they could record or process.

Naiades will differ from current technologies in two very important ways. First, the system will be an internet of control area networks connected through wireless gateways that link simple sensors — measuring things like temperature, conductivity, turbidity, flow, and ambient light — to bacterial sensors and bulk water samplers, which will measure major cations, anions, metals, and pesticides. Secondly, the system will feature underwater nodes and surface base stations, each with an embedded computer. The wireless ad hoc network formed by the base stations, the Naiades subnet, will be able to automatically reconfigure routing pathways based upon the local analysis performed by the sensors, individually and collectively.



A lake is the landscape's most beautiful and expressive feature. It is the earth's eye; looking into which the beholder measures the depth of his own nature.

— Henry David Thoreau, *Walden*

Information gathered by the system could be used for immediate needs, such as issuing alerts to the appropriate agencies of increased E. coli levels in beach areas or for long-term research projects. Field tests, scheduled to begin

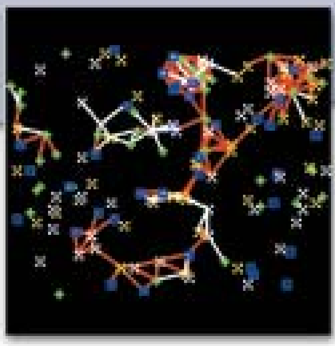
The Multidisciplinary Microprocessor

Thomas R. Szarek, a graduate student in the Department of Aerospace and Mechanical Engineering, loads a student designed microcontroller-based system featuring two sensors into a model rocket. Using the microcontroller, undergraduates in the department can measure the acceleration and velocity of the rocket as it is launched and determine its final height. Szarek, working with Professor Patrick F. Dunn and Thomas C. Corke, the Clark Equipment Professor of Aerospace and Mechanical Engineering, has developed the rocket project in order to focus on the use of embedded systems for data acquisition. Undergraduates build on this project and the concept of using microcontroller-based systems throughout their studies with an effort culminating in AME 441: Senior Design, when they design and build an airplane and program it to fly autonomously.

Throughout the course of their studies, undergraduates in the Department of Aerospace and Mechanical Engineering learn how to design aircraft. As important, they learn how to design and build a series of microcontrollers – tiny embedded systems operated by rechargeable batteries – that features a global positioning system, accelerometers, pressure transducers, thermocouples, an analog-to-digital converter, and a transmitter. The purpose of designing these microprocessors is two-fold: to introduce undergraduates to the interdisciplinary nature of engineering today via the building block of all mechatronic systems and to address real-world applications. This is particularly important, says graduate student Thomas R. Szarek, "because digital processors are finding their way into more and more, and smaller and smaller, technologies."

According to **Thomas C. Corke,** the Clark Equipment Professor of Aerospace and Mechanical Engineering, there is an increasing need for remote controlled aircraft, particularly for data collection. "The obvious need is a military one for reconnaissance and tracking, such as the drone planes that flew over Iraq. By using remote piloted aircraft for these types of missions, human lives were not put at risk," says Corke.

"But there's also a lot of interest in using these autonomous aircraft as environmental monitors," he says. In fact, one of Corke's students is conversing with the forestry service in Florida about the possibility of using a remote piloted plane to follow migratory animals. The embedded system in such a vehicle could trace the paths of animals tagged with radar transmitters, but it could also track them visually via an embedded pattern recognition program. In addition, these aircraft could be used to measure air and water quality. And, using infrared sensors, they could monitor thermal pollution. "The idea," says Corke, "is that all the information is gathered by the embedded system and then transmitted to a receiver on the ground. It's less expensive than sending up manned flights, and, because of that, it would be possible to operate more aircraft, cover larger areas, and collect more data."



Graduate student Bren Mochocki is working with Gregory R. Madey, associate professor of computer science and engineering, to develop an agent-based simulation of an ad hoc sensor network. The goal of this project is to help identify the types of routing protocols useful in a network while also tracking how messages flow through a network. The graphic shown above was captured from one of the simulations run using Mochocki's research.

in year three of the project, will focus on detecting, forecasting, and monitoring storm events and diel (day/night) fluctuations.

The Naiades project also includes several educational objectives. A learning module will be developed for the University's first-year engineering course sequence. Information from the project will also be incorporated into the curriculum of CE 498/598: Introduction to Environmental Engineering and Science and a graduate course on water-rock interactions. Graduate students involved in the project will participate in a one-credit-hour interdisciplinary special topics course to be taught by project faculty. And, an interdisciplinary workshop on environmental sensors will be held on campus during the final year of the project.

Perhaps one of the most attractive elements of this interdisciplinary effort is that researchers will not have to travel far to find a natural laboratory in which to test the system they are creating. The Naiades system will first be tested in the two lakes on campus, St. Mary's and St. Joseph's, in order to develop accurate predictive models of algal blooms, an important environmental question that would benefit from the high-resolution, real-time data collection offered via the Naiades system.

Unfortunately, the solution — using embedded systems to better monitor the real world — is not as straightforward as it seems. "Embedded processors and their proliferate use, such as the development of the Naiades project," says Antsaklis, "is driven by the fact that we are able to cheaply manufacture these devices. But, you cannot simply set out a group of processors and expect them to act together in a coherent fashion in relationship to the real world. It simply will not happen without a tremendous amount of planning and a detailed understanding of hybrid dynamical systems."

According to Antsaklis, when a system is distributed, so is the information. No single node contains all the information, and no single node acts as the command center. "The traditional notions of communications are challenged," he says. "One of the first considerations in a network is to establish a path along which the nodes communicate. In addition, there is a lot of protocol software that needs to be written or refined to ensure that the processors are synchronized with one another and with the real world. And, finally, because they are out in the real world ... some of them miles away from a power source ... they need to be able to operate on small batteries or solar power." These are some of the issues being addressed by the Naiades team.

Under the supervision of Professor Panos J. Antsaklis and graduate student Luis Montestruque, seniors Kevin McGirr, shown here, and Travis Cuprak use wireless embedded controllers to coordinate the movements of two model helicopters.

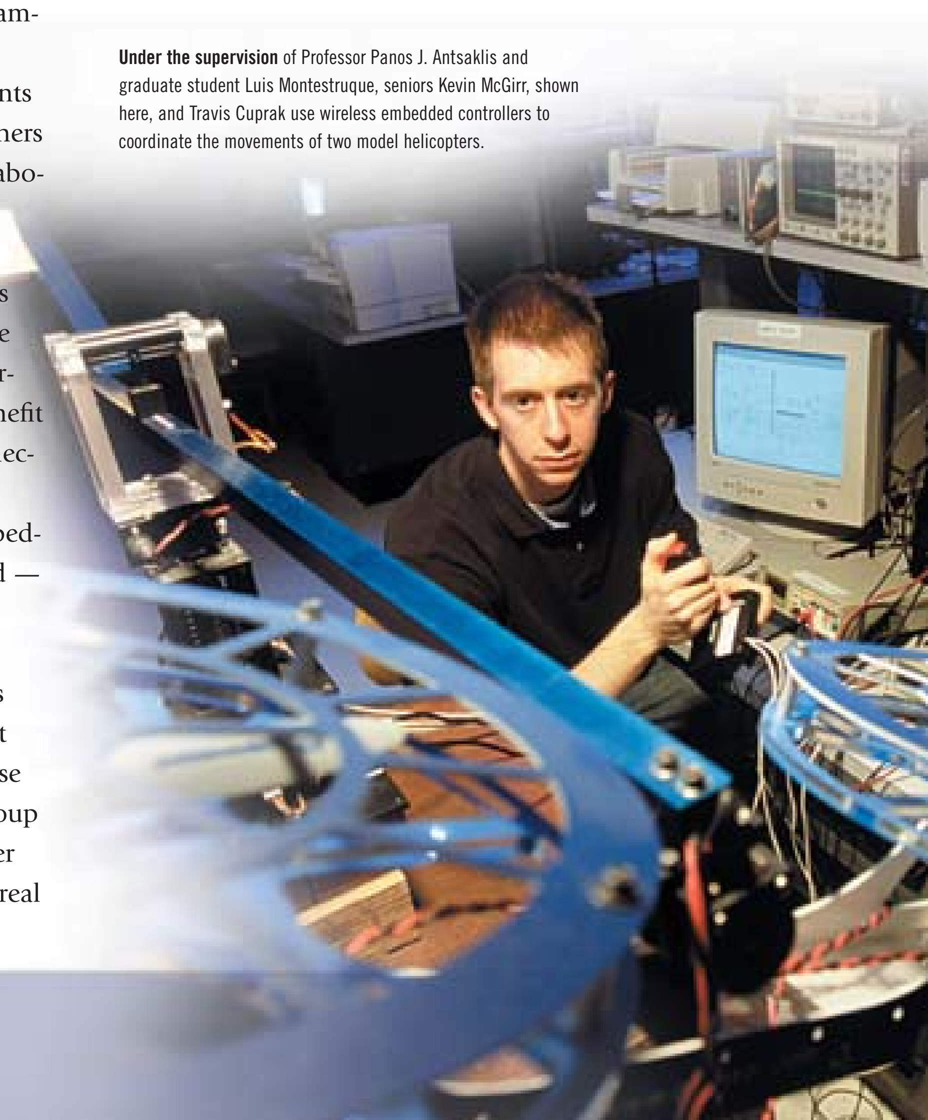
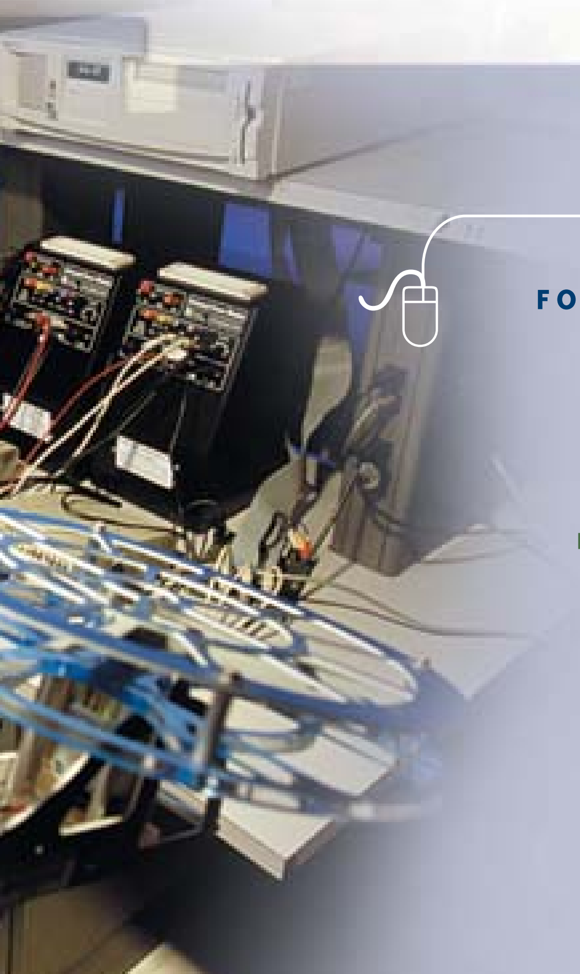


Photo: Heather Gollatz

In Greek mythology the Naiades — nymphs of rivers, lakes, streams, brooks, and marshes — were often imbued with supernatural powers and worshiped in conjunction with the gods of healing, fertility, and growth. At Notre Dame Naiades is the title of an embedded sensor network project designed to monitor the hydrology and ecology of freshwater lakes and streams. The project, focused on developing predictive models of algal blooms, will study St. Mary's and St. Joseph's lakes on campus. Using a networked array of sensors, faculty and students — such as Professor Patricia A. Maurice, left, and Leilani Arthurs, a graduate student in the Department of Civil Engineering and Geological Sciences — will monitor temperature, conductivity, algae biomarkers and by-products, and light in order to determine the trigger mechanisms for algal blooms and to develop and verify high-resolution spatio-temporal models of algal blooms and decays.

When they are successful in developing these intelligent sensors and flexible embedded systems, they will have made a quantum leap in environmental monitoring. This knowledge can then be applied to defense systems, to health monitoring, to the coordination of satellites or traffic systems ... the list is endless. But, the change is inevitable. The novel ways University researchers are employing networked embedded systems to collect data will usher in improvements to the way skyscrapers are designed, aircraft are built, and the environment is monitored. These changes may not inspire a 21st-century Sandburg or Thoreau to wax eloquent about the nodes, motes, or actuators, but the changes which will be implemented from the information gained will help build a better world.



FOR MORE INFORMATION ON NETWORKED EMBEDDED SYSTEMS TECHNOLOGY AND RESEARCH IN THE COLLEGE OF ENGINEERING, VISIT:

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LED Traffic Light Study Identifies Significant Benefits to Communities Making the Switch from Incandescent Lights

Most people fondly remember childhood games such "Red Rover," "Simon Says," or "Red Light-Green Light," the stoplight game where participants start and stop depending on the command barked out by the leader. Students in the Engineering Projects in Community Service (EPICS) program are looking at traffic commands in a much different light.

In fact, one of the EPICS groups within the College of Engineering is working with city engineers, community leaders, and transportation companies throughout Indiana to implement the replacement of incandescent traffic lights with light-emitting diode (LED) signals.

Shown are, left to right, Tom Silio, Michael Kramer, David Schwartz, Michael Bien, and Douglas Hall, associate professor of electrical engineering.

What the group has found is that, although the LED signals are initially more expensive, they use approximately 90 percent less energy than incandescent bulbs and last up to 10 times longer. Additionally, LED stoplights emit colored light instead of a white light filtered through a colored lens, enhancing the overall visibility of each signal.

Approximately 40 percent of the traffic signals in California have been switched to LED technology, but only 10 percent of the signals nationwide use LEDs. The students are currently performing analyses of the significant energy savings provided by the LED devices and studying methods of financing a community's initial investment in a switchover. They are also developing educational outreach tools for elementary and secondary school students that encompass LED lights and other energy-saving technologies, the role of engineering in society, and the importance of energy conservation to the environment.

Editor's Note: *The EPICS program, founded in 1995 at Purdue University, is designed to partner teams of engineering undergraduates with local service agencies. EPICS students are able to experience the design process from start to finish, develop management and leadership skills, learn to work on an often multidisciplinary team, and assist community organizations in reaching their goals in a timely and economic manner. The Notre Dame program, which has partnered students with local organizations since 1997, is one of six EPICS programs in the country.*