John Edwards

Signal Processing Drives a Medical Sensor Revolution

Sensor technology's impact on health care is growing rapidly. New applications are appearing almost daily. Wireless sensors are now used in an ever-growing number ways, such as monitoring glucose levels in diabetics, recording and tracking heart irregularities, and diagnosing infectious diseases. Linking sensors to mobile phones has made wearable sensors a reality, allowing individuals to monitor not only chronic diseases but also their lifestyle activities.

"There's a lot happening in health monitoring," says Andreas Spanias, a professor in the Arizona State University School of Electrical, Computer, and Energy Engineering. "Integrated sensors, on mobile phones, for example, can monitor vital signs, such as heart rates, breathing activity, oxygenation, and blood pressure," says Spanias, who is also the founder and director of the university's Sensor Signal and Information Processing (SenSIP) Center, a National Science Foundation (NSF) Industry and University Cooperative Research Center (NSF/UCRC).

Spanias says that signal processing is essential to optimal sensor operation and performance. "Our industry collaborators build inexpensive sensors, and signal processing improves precision and event detection using machine learning and fusion," he notes. "Even if the data is noisy or contains artifacts, signal processing can reduce noise effects. Signal processing algorithms, for example, will make wireless health monitoring more accurate and reliable. Signal processing makes it possible to use data from several sensors and combine the information appropriately to maximize the probability of correct detection."

Signal processing algorithms are likely to become even more essential to wireless health-care sensor development in the years to come. The technology is now entering a new phase made possible by the development of microscopic nanosensors and nanorobots designed for insertion into bodily tissues and the bloodstream. "With so many sensors in the body, and the large volumes of data they will be transmitting, how do you fish out the information that you need?" Spanias asks. "Signal processing and biomedical informatics will have a big role in that area, and algorithms will enable reliable prediction of disease and incentivize healthy lifestyles."

[LINKING SENSORS TO MOBILE PHONES HAS MADE WEARABLE SENSORS A REALITY, ALLOWING INDIVIDUALS TO MONITOR NOT ONLY CHRONIC DISEASES, BUT ALSO THEIR LIFESTYLE ACTIVITIES.]

INTRABODY NETWORKS

A system of wirelessly networked intrabody sensors and actuators could lead to revolutionary new applications in health-care monitoring, potentially creating innovative approaches to the treatment of an almost endless number of diseases, both major and minor. Yet an important obstacle to the development of reliable intrabody sensor/actuator networks is the fact that most health-care sensor network research to date has focused on communication along the body surface via devices linked through traditional electromagnetic radio-frequency (RF) transmissions. Such technology has significant limitations for intrabody system developers, however, due to the physical nature of propagation within the human body, which is composed primarily of water, a medium through which RF electromagnetic waves do not easily propagate.

Researchers at Northeastern University in Boston, in collaboration with researchers at the University of Catania and the Sapienza University of Rome, are hoping that by taking a novel approach to wireless sensor communication—ultrasonic networking technology—they can make intrabody sensors and actuators an accurate and reliable technology.

The researchers are currently pursuing a closed-loop combination of mathematical modeling, simulation, and experimental evaluation to determine the practicality of using ultrasonic networking in human tissues. "A major challenge is creating a waveform that's resistant to the effects of multipath and scattering," says team member Tommaso Melodia, an associate professor in Northeastern University's Department of Electrical and Computer Engineering.

The magnitude and direction of a reflected wave depends on the orientation of the boundary surface as well as on the acoustic impedance of the tissue. Scattered reflections happen whenever an acoustic wave encounters an object that's relatively small in relation to its wavelength or meets a tissue with an irregular surface. "At the receiver, basically, you receive a combination of multiple replicas of the same signal," Melodia says. "You have to create a receiver that can differentiate between these various signals; it basically needs to be able to record the original signal from multiple replicas that it's receiving."

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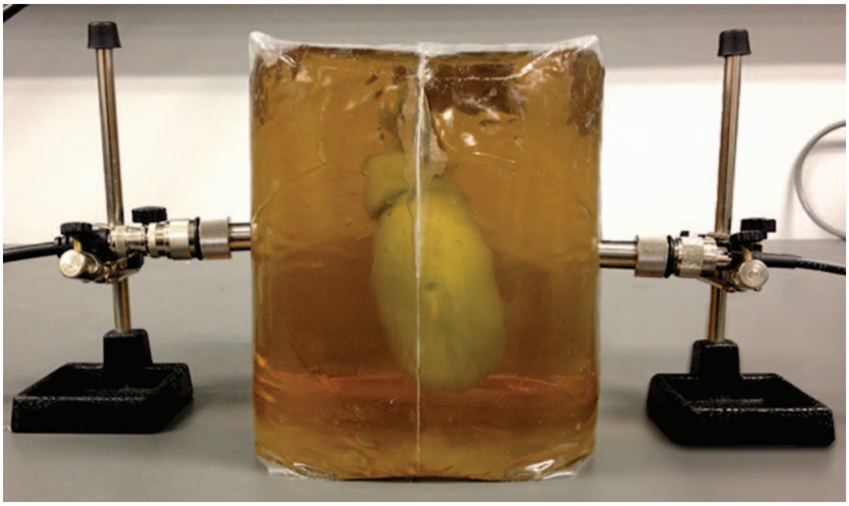


[FIG1] **A synthetic kidney was used in preliminary tests at Northeastern University to evaluate various ultrasonic communication technologies and configurations. (Photo credit: Northeastern University.)**

Signal processing is also essential for creating receivers that can cope with an onslaught of data coming in from large numbers of ultrasonic sensors floating inside a body. "Basically, solving some mathematical optimization problems gives us the best way to share the channel between different devices that are trying to transmit at the same time," Melodia explains.

Early in their investigation, the researchers proposed basing their ultrasonic intrabody network on ultrasonic wideband (UsWB), a relatively new multipath-resilient physical and medium access control (MAC) layer integrated protocol. UsWB is the only MAC protocol specifically designed for ultrasonic intrabody sensor networks, while a wide variety of MAC protocols designed for traditional RF-based wireless networks are currently available.

According to the researchers, UsWB is based on the concept of transmitting short carrierless ultrasonic pulses following a pseudorandom adaptive time-hopping pattern, featuring a superimposed adaptive spreading code. After testing the protocol, the researchers were able to show that UsWB enables nodes to flexibly trade data rate performance for power consumption while allowing multiple concurrent sensors to coexist by dynamically adapting their transmission rate to channel and interference conditions.

Recently, the researchers compared the performance of UsWB with a pair of existing MAC protocols originally designed for use with RF-based wireless networks: ALOHA and carrier sense multiple access (CSMA). Their tests showed that UsWB generally outperforms ALOHA in terms of throughput, although CSMA can achieve comparable performance under certain kinds of setups. Additionally, according to the researchers, ALOHA and CSMA both exhibit very high packet drop rates compared to UsWB, which always keeps the packet drop rate below a given threshold. The tests also found that UsWB performs better than either ALOHA or CSMA in terms of short-term fairness, average packet delay, and delay variation. Finally, the researchers discovered that CSMA has the highest energy consumption per bit, due to long idle listening times. UsWB's bit cost, on the other hand, is the lowest and can be further reduced by trading throughput for energy consumption through energy-minimizing rate adaptation, the researchers say.

Testing various intrabody network system technologies and configurations required creating an environment that mimicked real-world conditions. "We used some devices known as medical phantoms," Melodia says. For this particular project, the phantoms were synthetic devices designed to produce the basic ultrasound characteristics of real tissue. "We've used mostly kidneys so far," Melodia says. "We have a synthetic kidney that we transmit information through" (Figure 1). The next step is building a miniaturized prototype of the transceiver. "We have a prototype that works well, but it's big," Melodia says. "We want to build a miniaturized platform that will be able to do what we're doing now, but be much smaller and can be implantable.

Melodia predicts that an intrabody network system could become available for general use within a decade. "It will take a lot of work, but that seems like a realistic possibility," he says.

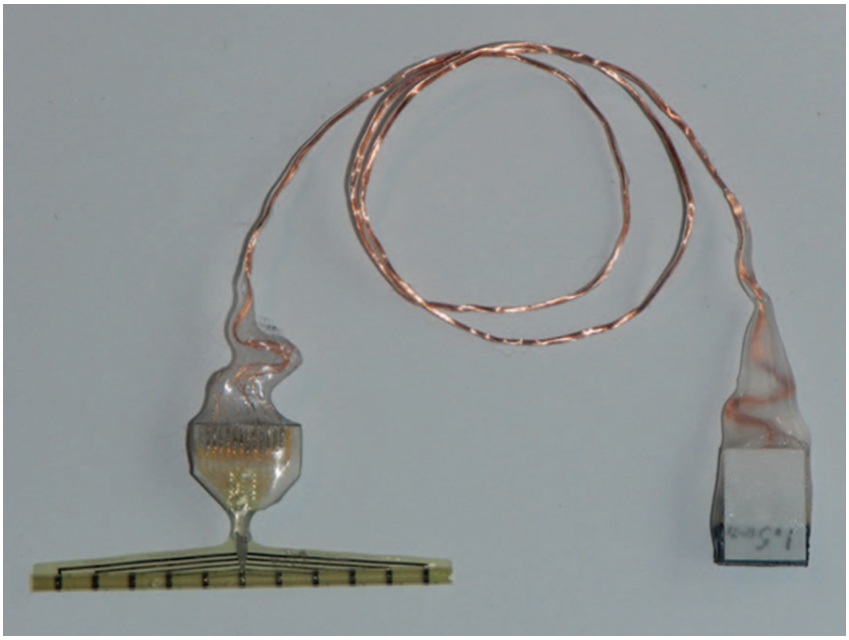
NEURAL RECORDING SENSORS

A research group in the University of Bath's Centre for Advanced Sensor Technologies (CAST) is investigating the use of implantable devices for electroneurogram (ENG) signal recording, potentially increasing the quantity and quality of received information. An ENG is used to visualize directly recorded electrical activity of neurons in the central nervous system (brain and spinal cord) or the peripheral nervous system.

Reliably collecting neural data is a goal that has eluded numerous researchers for many years. "Nerves tend to come in bundles of hundreds or thousands and carry neural traffic to different destinations to and from the central nervous system," says John Taylor, CAST's head and a professor in the University of Bath's Department of Electronic and Electrical Engineering. Identifying individual pathways and the traffic on them is difficult. "Several years ago we invented a technique called velocity selective recording (VSR) that, we believe, goes some way to solving this problem," Taylor continues.

Working with project collaborators, including University College London, the University of Cambridge, the University of Freiburg, and Aalborg University, the Bath researchers developed a range of implantable electrodes and amplifiers to test a technique that Taylor says is essentially a simple signal processing concept.

"Our recording technique provides real-time velocity spectral analysis of activity on a nerve," Taylor says. In practice,



[FIG2] **A multielectrode nerve cuff used for velocity-selective recordings made by Martin Schuettler, a senior scientist at the University of Freiburg and chief technology officer of CorTek, a Freiuburg, Germany-based developer of a neurotechnological platform for measuring and stimulating of brain activity. (Photo credit: Martin Schuettler.)**

such a nerve might contain hundreds or thousands of individual fibers [axons], with signals propagating over a wide range of velocities (up to 120 m/s in humans) in both directions. "This (technique) should be useful because neural propagation velocity and fiber diameter are generally related, so an analysis of activity by velocity and direction is equivalent to knowing the diameters of the nerves that are excited at that time," Taylor says. "Anatomy then allows us to link this to function."

In the future, Taylor says these function-specific signals might be used to design systems for controlling neuroprosthetic devices, such as providing a neural stimulator with a feedback loop for bladder control to treat urinary incontinence. "Currently available methods to provide the information we seek tend to rely on fairly classical pattern processing methods, such as clustering and principal component analysis under the generic title of 'spike sorting'," Taylor says. Such methods tend to be computationally intensive and therefore unattractive for implantation. "In addition, some form of training is generally required and may be impossible or impracticable," he adds. By contrast the signal processing required for VSR is computationally simple, power efficient and lends itself to real-time working.

Taylor says that signal processing is a key building block in the group's research. "This is because surgical considerations impose strict limits on the size and complexity of our implanted devices and hence on the sensitivity and resolution of our basic signal acquisition capability," he explains. "Signal processing can compensate for this and is used wherever possible for filtering noise, performing spectral analysis of waveforms, and ultimately for decoding the impulses that we record from the nervous system."

According to Taylor, VSR requires multiple samples of the composite propagating neural signal. Such samples are typically provided by a multielectrode cuff (MEC) placed around the nerve (Figure 2). The MEC, which is an insulating cuff typically 2–3 cm in length and containing 10–12 electrodes, is an extension of the traditional tripolar type of nerve cuff that has been implanted in many patients successfully for several decades, Taylor says.

The samples are identical but delayed by a period that depends on both the cuff geometry and the propagation velocity of the signal. To construct the velocity spectrum from this data an operation called "delay-and-add" is applied. The operation adds artificial delays that cancel the natural delays in each channel before finally adding all the signals together. "When the artificial delays are equal to the naturally-occurring ones, the spectral output passes through a peak (local maximum) indicating the presence of an excited population of axons at that velocity," Taylor says. "This is the simplest approach to VSR and the resulting spectrum is called the intrinsic velocity spectrum (IVS)." The method, he notes, is closely related to various beamforming algorithms employed in radio and radar antenna systems.

Unfortunately the method achieves relatively poor velocity selectivity, Taylor says. It has particular difficulty in distinguishing closely spaced velocity peaks. Various additional techniques have been developed to improve the velocity selectivity including the use of bandpass filters and time delay neural networks (TDNNs), Taylor explains.

One of the biggest limitations inherent in existing neural signal processors is the requirement to build complex statistical models. "These models are not only computationally expensive to produce but also require a good deal of time to 'learn' as they become patient-specific," Taylor says. "To overcome these limitations we considered an entirely different signal processing approach, based on conduction velocity instead of pattern shape."

Noise poses another challenge. "The signals we record are from biological sources and so are often very noisy," Taylor remarks. "It is not uncommon for the signal-to-noise ratio (SNR) to be less than 0 dB, and so innovative methods must be developed to extract information." Coupled with the requirements for real-time operation and good long-term stability, the challenges are not insignificant.

Recording neural activity from an intact nerve represents another highly challenging task, due to the poorly understood nature of the electrode-tissue interface and the associated problems of handling very small signals. “We have worked extensively to improve electrode and amplifier designs so as to stabilize the electrode characteristics and maximize the possible recorded SNR,” Taylor says.

Taylor notes that the group’s signal processing algorithms are still incomplete. “So far, we have been recording and analyzing electrically evoked ENG—neural signals produced by electrical stimulation,” he says. “This is an interesting and useful exercise, but is an approximation in several ways to natural neural recording.”

According to Taylor, the amplitude and SNR of the recorded signals are much larger than in comparable natural signals. Additionally, information such as pressure or joint angle are encoded in neural firing rates, so identifying the source and direction of a neural signal is only part of the overall package necessary to create a complete recording system.

“The impulses generated by electrical stimulation—compound action potentials (CAPs)—are synchronized to the stimulating pulse, so their arrival times are predictable,” Taylor says. “The signal processing algorithms required to interpret them are, therefore, essentially time invariant and therefore relatively simple.” Taylor notes that the researchers have recently begun modifying their VSR algorithms to include time dependence, including the ability to identify not just the velocity and direction of neural traffic but also the number of impulses in a particular velocity band arriving per second. “This has required the inclusion of statistical methods in our algorithms that we refer to as velocity spectral density (VSD),” he says.

> THE RESEARCHERS ARE NOW LOOKING TO EXTEND THEIR WORK, WHICH TO DATE HAS INCLUDED ONLY SINGLE ACUTE EXPERIMENTS, TO EXTENSIVE LONG-TERM CHRONIC STUDIES IN NONHUMAN MODELS.

The researchers are now looking to extend their work, which to date has included only single acute experiments, to extensive long-term chronic studies in nonhuman models. “To achieve this, we must overcome the surgical, mechanical, and electrical challenges that are associated with long-term implantation of electronic devices,” Taylor says. “New methods will need to be devised to handle communications and power concerns.”

Since the project is still in a developmental stage, seeking commercial interest would be premature, Taylor says. “However we have good links with the United Kingdom’s largest commercial manufacturer of implanted medical devices, indeed the only company licensed to produce implantable electronics in this country, and they are aware of and interested in our project,” he says. “However, before giving it to a company for development, we have still to prove conclusively that VSR is clinically useful.”

Yet Taylor is optimistic that the research will ultimately lead to a widely used medical technology. “We have tested the method in animals, and our results are quite promising so far, although we feel we are still a long way from a human implant that could be generally adopted,” he says.

AUTHOR

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[society **NEWS**]

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The IEEE James L. Flanagan Speech and Audio Processing Award will be presented to Stephen John Young “for pioneering contributions to the theory and practice of automatic speech recognition and statistical spoken dialogue systems.” This award was founded and is sponsored by the IEEE SPS.

The IEEE Fourier Award for Signal Processing will be presented to Georgios B. Giannakis “for contributions to the theory and practice of statistical signal processing and its applications to wireless communications.”

The IEEE Donald O. Pederson Award in Solid-State Circuits will be presented to Robert Whitlock Adams “for contributions to noise-shaping data converter circuits, digital signal processing, and log-domain analog filters.”

IEEE medals are the highest honor of awards presented by the IEEE. The medals will be presented at the 2015 IEEE Honors Ceremony at ICASSP in Brisbane, Australia. Three SPS members were awarded with IEEE medals for 2015:

The IEEE Edison Medal recognizes a career of meritorious achievement in electrical science, electrical engineering, or the electrical arts. James Julius Spilker will be honored “for contributions to the technology and implementation of civilian GPS navigation systems.”

The IEEE Jack S. Kilby Signal Processing Medal, awarded for outstanding achievements in signal processing, was presented to Harry L. Van Trees “for fundamental contributions to detections, estimation, and modulation theory; sensor array processing; and Bayesian bounds.”

The IEEE James H. Mulligan, Jr. Education Medal, distributed for a career of outstanding contributions to education in the fields of interest of the IEEE, was awarded to Richard Gordon Baraniuk “for fundamental contributions to open educational resources for electrical engineering and beyond.”