Brain-Computer Interfaces: Where Human and Machine Meet

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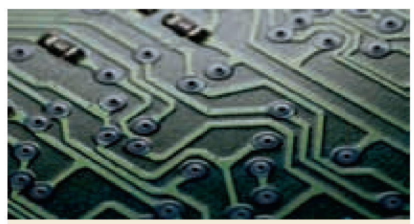
For a long time, researchers have been working on a marriage of human and machine that sounds like something out of science fiction: a brain-computer interface.

BCIs read electrical signals or other manifestations of brain activity and translate them into a digital form that computers can understand, process, and convert into actions of some kind, such as moving a cursor or turning on a TV.

Several academic and corporate researchers are now working to commercialize the technology, while other projects are taking innovative approaches to BCIs that could create interesting products or services in the not-too-distant future.

The technology holds great promise for people who can't use their arms or hands normally because they have had spinal cord injuries or suffer from conditions such as amyotrophic lateral sclerosis (ALS) or cerebral palsy. BCI could help them control computers, wheelchairs, televisions, or other devices with brain activity.

There is even a research effort underway to use BCI as the basis for brainwave-based biometric authentication. The reaction of users' brains to a stimulus of some sort would determine whether they could, for example, access a computer or enter a building.



Thus, BCI has generated interest as an approach that could yield revenue in the marketplace.

However, the technology has a long way to go before it can be used widely, as it still faces problems such as user acceptance and signal accuracy.

BCI BACKGROUNDER

BCI research includes disciplines such as nanotechnology, biotechnology, information technology, cognitive science, computer science, biomedical engineering, neuroscience, and applied mathematics.

History

Scientists have been actively researching BCI since the early 1970s. At that time, Jacques Vidal, now a University of California, Los Angeles, emeritus professor, led the university's federally sponsored Brain-Computer Interface Project.

Over time, researchers have experimented with implanting simple BCI sensors within rats, mice, monkeys, and humans.

In the late 1990s, researchers at the Georgia Institute of Technology and Emory University demonstrated BCI's medical potential by implanting an electrode in the motor cortex of a patient who was paralyzed below the neck and unable to speak. The technique let the patient communicate by moving a computer cursor.

In 1999, scientists at the MCP Hahnemann School of Medicine and Duke University Medical Center trained rats to use their brain signals to move a robotic water-dispensing arm.

Invasive versus noninvasive approaches

There are two principal BCI approaches: *invasive* techniques, which implant electrodes directly onto a patient's brain; and *noninvasive* techniques, in which medical scanning devices or sensors mounted on caps or headbands read brain signals.

Both approaches have drawbacks, according to University of Southern California professor Theodore Berger, chair of the World Technology Evaluation Center's Panel on Brain Computer Interfaces.

Noninvasive approaches are less intrusive but can also read brain signals less effectively because the electrodes cannot be located directly on the desired part of the brain. Invasive techniques, however, require surgery and carry the risk of infection or brain damage.

Moreover, noninvasive approaches' ability to read signals from many points in the brain could help identify a wider range of brain activity. This would be helpful because the cells that address the multiple types of motions and movement of various body parts are in different parts of the brain, noted Berger.

However, he added, processing the large amount of data that neurons in multiple parts of the brain would generate would be difficult for BCI systems.

NEW BCI APPROACHES

Several companies and universities are conducting important research in various BCI-related areas. For example, scientists at the Laboratory of Brain-Computer Interfaces at Graz University of Technology's Institute for Knowledge Discovery are using BCI to help patients control a prosthesis, said postdoctoral researcher and lecturer Gernot Müller-Putz.

NeuroSky is working on BCI applications for healthcare providers, including treatments for attention deficit disorder, and for the entertainment industry, including video games and toys, said company spokesperson Johnny Liu.

Cyberkinetics and Brown: An invasive approach

Cyberkinetics Neurotechnology Systems has developed the BrainGate Neural Interface System, a medical device designed to help patients with spinal cord injuries or other types of motor impairment control a computer with their thoughts.

BrainGate is based on research conducted by Brown University professor John Donoghue, who is Cyberkinetics' founder and chief scientific officer.

His research focuses on deciphering the way the brain turns thought into the signals that cause actions such as arm movement. For example, he explained, when a person wants to move an arm, millions of neurons emit pulses in a complex pattern that the spinal cord reads and translates into a signal that controls the muscles.

Using multielectrode recording arrays and functional magnetic resonance imaging (fMRI) techniques, Donoghue's research team has captured subjects' brain signals and then used digital signal processors (DSPs) and algorithms to translate them into a format that a computer can understand and process.

The subject must first enter an MRI scanner. The scanner creates a magnetic field and uses radio signals to capture the brain's hemodynamic responses to the person's thoughts about moving, for example, a cursor or prosthesis. The hemodynamic responses include increased blood flow and hemoglobin supply to the neurons that are actively working.

Cyberkinetics used the BrainGate system in a clinical trial that helped a volunteer patient paralyzed from the neck down perform activities such as playing Pong or controlling a TV.

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A surgeon implanted a small microelectrode array in the patient's motor cortex, an area located on the brain's frontal lobe that helps controls movement by sending signals through the spinal cord to the body's limbs.

The 4 × 4 mm array is equipped with 100 silicon microelectrodes that simultaneously sense and transmit the electrical impulses from multiple neurons. Focused thought by the patient about moving something yields a specific pattern of strong neuron firing and electrical spikes.

The signals travel to a titanium connector attached to the skull and then via fiber-optic cabling to amplifiers that augment the signals and route them to a computer, which processes them and turns them into the desired output.

BrainGate is undergoing two further clinical trials, one seeking to restore limb movement in patients with spinal cord injuries, strokes, and muscular dystrophy; and another looking to enable communication in patients suffering from motor neuron diseases such as ALS. The company expects to launch the system commercially in 2008 or 2009.

Eventually, Cyberkinetics hopes to augment the system to wirelessly send brain signals to amplifiers and then a computer, which would eliminate the need for connectors and cables, said company president and CEO Timothy Surgenor.

Wadsworth Center: A noninvasive approach

The New York State Public Health Department's Wadsworth Center, a public health laboratory, is using a noninvasive electroencephalogram (EEG) cap to acquire brain signals by recording neuronal electrical activity.

The research team—led by Jonathan Wolpaw, chief of Wadsworth's Laboratory of Nervous System Disorders and a University of Albany professor—has developed the BCI2000 research system.

The BCI2000 uses an EEG cap, which includes up to 200 electrodes that are placed on the scalp along with conductive paste to aid in the capture of electrical signals emitted by neurons in the brain.

The system uses a 16-channel biosignal amplifier to boost the captured signals. Its DSPs then extract and measure signal features, which a digitizer prepares for computer processing.

To maximize the system's effectiveness, Wolpaw said, the researchers train subjects how to exercise some control over their brain's electrical signals.

One Wadsworth implementation helps people with speech problems communicate via the P300 brainwave, a positive voltage that shows up in an EEG shortly after a subject experiences an unexpected or significant sensory stimulus. The brainwave doesn't contain information but instead enables Wadsworth's system to detect the subject's desire to communicate in some way.

Patients watch a random sequence of letters or images, and when they see the one they want to communicate, their P300 brainwave spikes. The BCI2000 detects the spikes and registers the corresponding image or letter.

This process is currently slow—two to four words per minute—because the system requires time to collect signals from multiple areas of the brain, segregate the signals that come from the relevant neurons, and translate them appropriately into actions, noted Wolpaw.

He said Wadsworth researchers are working to make the system faster by designing better signal-analysis methods.

The group wants to establish a nonprofit foundation to make the system available to people who need it, he noted.

Honda: MRI technology

Japan's Honda Motor Corp. and ATR Computational Neuroscience Laboratories recently used brain signals to control a robot's simple movements.

Participants positioned within an MRI scanner move their hand or fingers in a certain way, explained ATR researcher Yukiyasu Kamitani.

As in Cyberkinetics' system, Honda's scanner detects the subject's brain signals. The system sends the MRI signals over Ethernet cables, via TCP/IP, to a computer, which processes the information and then uses software to issue commands that operate a robotic hand.

If the participants in the scanner make a fist or spread their fingers, the robotic hand does the same, as Figure 1 shows.

In the next 10 years, said Honda spokesperson Sachi Ito, the company could utilize this research to improve the company's popular Asimo walking robot, used extensively in public relations and advertising campaigns.

In the distant future, the technology might generate auto-safety innovations. For example, Kamitani said, the system could decode driver intentions, such as the direction in which they want to turn, and communicate them to other drivers and pedestrians.

Figure 1. Honda Motor Corp. has developed a BCI system that can operate a robotic hand. When a subject moves a hand or fingers, the system's MRI scanner detects the brain signals, processes them, and uses software to command a robotic hand to move the same way.

Currently, though, he noted, portability is an issue because MRI machines weigh several tons.

Stanford University: Detecting movement planning

Stanford University BCI researchers are looking for ways to identify the signals the brain makes when it is planning to direct the body to move a certain way. These occur before the signals the brain makes when it actually directs a specific movement.

"Every time we move, we first plan that movement," explained Stanford assistant professor Krishna Shenoy, director of the university's Neural Prosthetic Systems Laboratory. "Understanding [neural] planning activity is of central importance for guiding prosthetic limbs because it can tell you where the arm should end up even before you start moving it."

Knowledge of the brain's planning activities could dramatically improve mathematical estimations of how the arm should move and yield systems that are faster and more accurate, said Shenoy.

Therefore, his team is investigating how neurons in the brain's parietal reach region plan and guide arm movements.

Shenoy's group hopes to use its research results to develop effective prostheses, as well as systems that help users communicate or control devices.

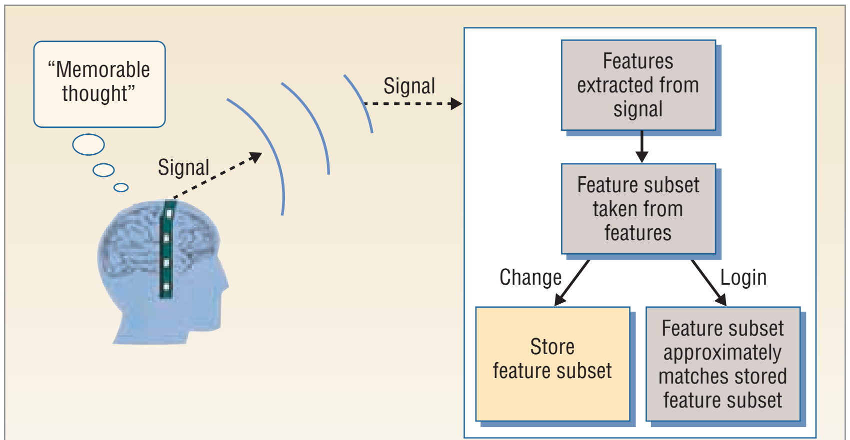
Columbia University: Image search

Scientists at Columbia University's Laboratory for Intelligent Imaging and Neural Computing (LIINC) are creating a BCI system designed to search through images much faster than humans or computers can on their own.

The federally funded research could help law-enforcement officials search through video and quickly identify criminals, terrorists, or suspicious activity.

The Cortically Coupled Computer Vision (C3Vision) system utilizes the brain's ability to recognize novel, unusual, interesting, or rare elements in images more quickly than humans can identify them, explained professor and LIINC director Paul Sajda.

The C3Vision system would show images very quickly to viewers chosen for their ability to recognize specific types of activity. For example, police officers could use the system to look for criminal activity, and radiologists could utilize it to detect



Source: Carleton University

Figure 2. In Carleton University's proposed BCI-based biometric system, subjects use specific thoughts as passwords (called pass-thoughts*). When someone tries to access a protected computer system or building, they think of their pass-thought. A headpiece with electrodes records the brain signals. The system extracts the signal's features for computer processing, which includes identification of the feature subset that best and most consistently represents the pass-thought. The biometric system then compares the subset to those recorded for authorized users.*

abnormalities in medical images such as mammograms.

A user wears an EEG cap that measures the electrical signals of neuron groups located in different areas of the brain. According to Sajda, the C3Vision system uses this information to recognize images in which the viewer has seen something novel or rare. It then ranks these images in importance, based on the strength of the viewers' brain signals.

This capability would mark a vast improvement over computer-vision systems, which lack the human brain's capacity to rapidly recognize familiar objects in various contexts, poses, or environments, Sajda said.

Helsinki University of Technology: MEG

Scientists at Finland's Helsinki University of Technology Laboratory of Computational Engineering's Cognitive Science and Technology Research Group are using an EEG cap to capture brain signals from users and help them control a virtual keyboard by simply thinking about hand movement.

The research group has also explored the use of magnetoencephalography (MEG), which measures the tiny magnetic fields generated by electrical activity in the brain. To determine what subjects want to do, MEG-based systems would have to interpret these magnetic fields, much like the way EEG-based systems interpret electrical signals.

The Helsinki scientists say they are interested in MEG because of its high sensitivity and good spatial and temporal resolution.

However, portability would be an issue because MEG machines are large devices and require positioning subjects inside them, as is the case with MRI scanners.

Carleton University: Biometrics

Canada's Carleton University is using a BCI system as the basis of a biometric identity-authentication device. This could replace traditional biometric methods, such as scans that compare a person's fingerprints or retinal patterns with those of authorized users of protected systems.

The Carleton approach uses the brain's response to stimuli, such as sounds or images, as the authentication method. Experiments indicate that EEG signals generated by the brain in response to a stimulus are unique to each person and thus have biometric potential, said Carleton doctoral student Julie Thorpe.

The researchers have not built a system yet, but conceptually, users wearing a headpiece with electrodes would press a button or key on a keyboard to start the biometric identification process, think of a thought that would act as their password (called a *pass-thought*), and then press another key to stop the procedure. The system would then record the brain signal emitted when the users produce the pass-thought and extract its features for computer processing.

When users want to access a protected system, they would produce their pass-thought. The biometric system would extract its features and compare it to those recorded for authorized users, as Figure 2 shows.

Unlike other biometric approaches, the Carleton system would let users change their identifier by changing the stimulus.

Neural Signals: Neurotrophic electrodes

Neural Signals has released a BCI-based speech-restoration project that uses surgically implanted neurotrophic electrodes to capture electrical signals from the brain's Broca's motor area. This area, which controls speech, is in the lower part of the frontal lobe.

The neurotrophic device induces neurites—which are projections from a neuron's cell body—to grow into the tip of the electrode, whose wires then transmit brain signals for recording and processing, according to Neural Signals chief scientist Phil Kennedy. This attachment between the neuron and the electrode creates long-term signal stability, he explained.

The researchers have identified which brain signals represent each of 39 English phonemes. The system can thus convert signals from the patient's brain into words.

The company charges $250,000 for a patient to restore communication via implanted neurotrophic electrodes, said Kennedy.

INTERFACE INTERFERENCE

Research is improving BCI technology. However, the approach faces numerous challenges to widespread use.

First, the technology is so new, researchers are still learning how to effectively implement it and adapt it to different patients, who have different needs and physical characteristics.

And until they are widely commercialized, BCI systems will tend to be very expensive, due to the use of sophisticated technologies. They also will be large, making them impractical for general usage.

BCI systems will have to be more automated for the approach to be widely adopted. The systems are complex to use and their readings can be difficult to interpret, thus requiring the involvement of experts.

In addition, said Stanford's Shenoy, technicians must be present to perform various tasks, such as plugging in connectors to brain implants, entering parameters needed for signal processing, and adjusting the processing to accommodate changing neural signals.

Moreover, users must learn how to use their thoughts to create the brain signals that generate desired actions in BCI systems, a process that can require weeks or months. This poses a considerable challenge to widespread adoption of BCI systems because subjects get frustrated and lose patience when the process takes too long, USC's Berger explained.

Another challenge, said Cyberkinetics' Surgenor, is that BCI commercial development is so new, many companies are not investing the time and money necessary for effective product development.

Signal accuracy

An issue with BCI technology, particularly noninvasive approaches, is the ability to accurately capture signals from the brain that indicate, for example, the direction in which patients want to move their arm.

Getting reliable readings of signals from sensors not in contact with the brain is difficult, according to Berger. He said attenuation occurs because signals must travel a distance from the neuron to the sensor.

In addition, he noted, a BCI system must read signals from a specific set of neurons related to a subject's thoughts, but when the sensors are outside the skull, it also picks up signals from other neuron sets.

Electrode performance

Invasive BCI systems can experience problems with their electrodes. The brain recognizes and tries to remove foreign objects, noted Berger.

When encountering foreign objects, the brain's glial cells reproduce rapidly and move quickly from one part of the brain to the affected area. For example, if a blood vessel breaks within the brain, glial cells move to encapsulate the broken vessel.

Thus, Berger said, when a surgeon introduces an electrode onto the brain, glial cells try to encapsulate it, which can attenuate signals and decrease system performance. Also, he added, the brain's inflammatory response could limit effectiveness.

The brain's response to the introduction of electrodes is a hot area of research, he noted. Current efforts focus on synthesizing peptides that form on the outside of neurons and coating electrodes with them, thereby fooling the body into accepting the electrodes as normal cells, he explained.

Applying drugs, such as rapamyacin, to electrodes could counter the brain's inflammatory response, a technique used with medical technologies such as heart stents, Berger said.

In the short term, BCI could help disabled people control computers, prostheses, wheelchairs, or other assistive systems.

Over time, researchers hope to make BCI systems less intrusive, more accurate, faster, and able to interpret and generate more complex actions.

If the systems become more compact, said ATR's Kamitani, they could even be used in everyday settings, for example, to operate keyboards and phones.

And in the distant future, BCI systems could help control complex robots or electrical probes implanted directly into muscles, assisting paralyzed or injured patients in moving their own limbs.

The systems could also help pilots or drivers by determining when they are experiencing cognitive overload and providing feedback that could ease the problem, said USC's Berger.

Automakers could put a BCI system into a vehicle's headrest to monitor drivers' brain activity and sound an alarm if they start dozing off.

The gaming industry, particularly in Europe, is also interested in BCI's potential for helping users to manipulate systems, he noted. Graz University of Technology researchers are experimenting with sophisticated, immersive virtual-reality systems that help people use BCI to move through complex environments by thought processes alone.

"In the long run," said UCLA's Vidal, "the increasing intimate coupling of external computing resources with brain function and behavior will find applications, some in quite unexpected directions." ■

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