Possible applications of neuroimplants

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Abstract: Brain machine interface (BMI) technology makes direct communication between the brain and a machine possible by means of electrodes. This paper reviews the existing and emerging technologies in this field and in the field of neuroimaging techniques.

Keywords: Brain computer interface, brain machine interface, neuroimaging, electroencephalography, magnetoencephalography, functional magnetic resonance imaging, neuromotor prosthesis.

1. Introduction

A few decades ago, implants that could interact directly with the central nervous system were exclusively a thing of science fiction. No longer. The last decade has seen astounding development in the technology known as brain machine interface (BMI). These implants connect the nervous system — via electrodes — to a machine, which makes communication between the two possible. Today BMIs are used as treatments for profound deafness, Parkinson’s disease and depression. Moreover, at the experimental stage, there are BMIs such as retina implants that can provide the blind with rudimentary visual orientation and, for the paralyzed, advanced prostheses maneuvered by neural control.

2. Existing Brain Machine Interfaces

A brain machine interface is a direct communication pathway between a brain and an external device. The first BMIs were deployed to extract information from the brain about neural activity that correlates to thoughts, emotions, or other mental states. This information can then be used to allow the user to control machines with mere mental efforts, or to allow machines to adapt to the needs of the user. The most widely used BMI is electroencephalography (EEG), which consists of external sensors that record electrical activity produced by neurons in the brain. Initially only used for diagnostic purposes, EEG is now used in a wide variety of simpler BMIs, due to its relatively low cost and non-invasiveness. Commercial applications of EEG include games and other recreational products that are controlled by thought commands. Emotiv Systems, a neuroengineering company headquartered in San Francisco, CA, has pioneered this market by releasing a game where the user can control the main character via an EEG device. EEG is also used to collect information in neuromarketing, a field that studies consumers’ cognitive and affective response to marketing stimuli.

Electroencephalography (EEG) is the practice of using electrodes placed directly on the surface of the brain to record electrical activity from the cerebral cortex. EEG an invasive procedure that requires a surgical incision in the skull to implant the device, but after implantation, can be used outside the surgery room (extra-operative EEG). However, because the electrodes are placed directly on the surface of the brain, EEG yields much more information than EEG. The level of detail of the information transmitted permits subjects to play computer games (Pong, Space invaders) with sheer mental efforts. However, EEG provides only superficial insights into the brain. Its activity is regulated by neuronal networks associated with different brain structures, some of them very deep inside the brain, such as the sub thalamic nucleus and the hippocampus. To decipher the activity of these deep structures, intracerebral electrodes have been developed. These are used for example to delimitate epileptogenic areas in epileptic surgery.
Thorough analysis of the neural patterns provided by ECoG has led to the possibility of neuroprostheses (NMPs). Experimental devices tested on non-human animals allow EEG to be used in NMPs that can replace or restore lost motor functions by routing movement-related signals from the brain to computers or machines. These are essentially arrays of microelectrodes that detect and register electrical activity (action potentials) via an electrode in direct contact with or close to one or more neurons. A digital sensor is programmed with the patterns of neural activity associated with various common motions, such as “move left arm up” and so on. These prostheses are mainly developed for therapeutic purposes, and motor control is still rudimentary. However, the main problem with these devices is the invasiveness of the implant and the likely long-term rejection related to glial scarring of the brain tissue. A possible way to deal with this problem is to employ a coating of carbon nanotubes around the microdevices. These may prevent the rejection of the implant.

BMI's that primarily feed information to the brain or alter neural activity by means of electrical impulses have been deployed in a wide variety of applications. In this category of implants we find cochlear implants and visual prostheses. These implants restore lost sensory perception by “translating” digital sensory data (from a microphone or a camera) to neural impulses that are transmitted to the brain. Whereas early cochlear implants could only convey sound to a limited degree, new “hi-fi” implants allow for listening to music and make it possible for the user to discern specific voices in loud rooms. Visual prostheses are much less developed. However, even here some progress is being made. A research group at Stanford University has developed a system for visual prosthesis that includes a subretinal photodiode array and an infrared image projection system mounted on video goggles. The resulting prosthesis provides stimulation with a frame rate of up to 50 Hz in a central 10° visual field, with a full 30° field accessible via eye movements. Pixel sizes are scalable from 100 to 25 μm, corresponding to 640–10 000 pixels on an implant 3 mm in diameter.

Other widely used implants include deep-brain stimulation (DBS), also referred to as “brain pacemakers,” and spinal cord stimulation (SCS). These involve the surgical implantation of a medical device in the brain or the spinal cord, respectively. These devices stimulate neural activity by electrical impulses. DBS and SCS have showed remarkable success in the treatment of certain types of chronic pain, Parkinson’s disease (by targeting the subthalamus nucleus), dystonia (globus pallidus pars interna), and essential tremor (thalamus ventralis intermedius). In the last few years, DBS has been expanded for use in the treatment of major depression, epilepsy and obsessive compulsive disorder. However, sometimes these implants have side effects in the form of unexpected behavior, such as outbursts of rage, sexual obsession or obsessive gambling, depending on the placement of the implant and the neural configuration of the patient. These side effects are not yet fully understood, but illustrate the potential of electrical stimuli of the central nervous system. DBS and SCS could in theory be used to induce or block specific emotional responses in unaware or unwilling subjects. However, DBS is at the moment only useful for affecting pathological conditions and not for the modulation of emotional states. Although DBS can neutralize abnormal brain activity, the effects of DBS on normal human brains is so far unknown and experiments to investigate them are not ethical in human patients, since the implant is too invasive.

It is very important to discern the difference between normal and pathological brain physiology. Whereas abnormal brains provide an easy target to focus on, the normal brain is much more difficult to decipher and to date very difficult to manipulate. Are we likely to see a more widespread use of DBS? Perhaps. This procedure is still risky and expensive, and only seems justified when medical
benefits are substantial. But as the size of the implant is reduced, and expertise in its use and implantation is refined, it may be used for the treatment of a wider array of psychological and psychosomatic disabilities or impairments, such as anorexia nervosa and obesity. However, it is unlikely to reach widespread use for non-medical (recreational or other) purposes, unless safety is dramatically improved and costs fall considerably.

3. Experimental technologies
At an experimental stage, we find BMI technology converging with the recent advancements in artificial intelligence (AI), a field in computer science that aims to create systems that can perceive and learn from their environment. The main idea is to link the brain to machines that can act on our thoughts but also learn from our behavior, and then act independently, foreseeing our needs. For example, some existing neuroprosthetic arms are controlled by the patient's thoughts in a quite crude way, crude in the sense that they require full attention and a great deal of effort. Experimental neuroprostheses are equipped with sophisticated sensors that mimic the constant sensory feedback to the brain from real organs. With an internal computer equipped with the appropriate AI, these prostheses co-adapt with the user, forming a "symbiotic" relationship. This opens up huge potentials not only for the field of neuroprosthetics, but also for our daily interactions with machines.

As machines get smarter and BMI technology develops, it is natural to assume that these technologies will converge. It is of particular interest to note the surprising plasticity of the brain. Even an adult or aging brain is able to "rewire" itself to new conditions. Studies of cochlear implants illustrate how the brain can adapt to better interact with BMIs. With a corresponding ability in intelligent machines, BMIs could allow us unprecedented levels of control not only in mechanical limbs, but also in vehicles, home utilities and tools.

A similar development seems likely to take place in the field of sensory neuroprostheses. A human eye is not a "dumb" object that simply channels visual data to our brains. The retina performs advanced and complex image processing to provide the brain with relevant and accurate visual input. The visual implants of today are far from that, more similar to digital cameras than to the complex sensory tools that our eyes are. However, research on equipping artificial retinas with some degree of "intelligence" is advancing rapidly. By applying filters and image processing, these smart implants can yield far better visual representations than "dumb" implants. These "intelligent" BMI devices open new possibilities for future development. Until now, cochlear implants and retinal implants have only been of interest to deaf and blind people, respectively. The sensory information provided is still vastly inferior to that provided by healthy eyes and ears. And without the use of AI and sophisticated computing, they are likely to remain so. With the convergence of AI and BMI however, these applications have the potential to be superior to our biological sensory equipment, in the sense that artificial eyes and ears may provide sensory input from infrared or ultraviolet light as well as sounds not audible to human ears. When this threshold is crossed, the commercial prospects of these technologies may be considerable.

DBS will potentially follow a similar development path. The first DBS models were, by modern standards, quite crude. In the development stage there are several DBS applications that include quite sophisticated sensory equipment that measures the levels of neurotransmitters such as dopamine and glutamate and thus adapt the strength and frequency of the electrical stimuli. This may prove highly valuable from the perspective of patient safety.
Of particular interest are those BMIs that create a connection between at least two brains via a BMI device. This allows communication, control or shared sensory information. Although these devices are still in an experimental stage, they are feasible and do not rely on any major breakthroughs. Consider a research project financed by DARPA, a research agency of the US Department of Defense. The project in question, Silent Talk, involves the use of EEG “to allow user-to-user communication on the battlefield without the use of vocalized speech through analysis of neural signals.” The basic principle is simple. The brain generates word-specific signals prior to sending electrical impulses to the vocal cords. These signals of “intended speech” are analyzed and translated into distinct words which are wirelessly transmitted as digital signals to a corresponding device in another brain. This translates the signals back to neural activity. If successfully deployed in the battlefield, it is not unlikely that this technology may be commercialized, as other military innovations have (the Internet, formerly ARPANET, was developed by DARPA). Other DARPA financed BMI experiments of a potentially dystopic nature involve the remote control of organisms. Experiments with rats show how BMIs could be used to remotely control animals’ actions and behavior. This could be achieved by directly manipulating motor control centers, a somewhat heavy-handed approach. A more subtle approach consists in triggering the reward center in the brain by releasing dopamine when “right” choices are made. DARPA is financing experiments that involve using sharks for naval reconnaissance. The sharks have BMIs that allow an operator to steer them toward a chosen target. It may be worth mentioning that DARPA is known for sometimes funding projects that are speculative with little scientific rigor. Whether or not these projects will result in anything tangible remains to be seen.

The rapid development of BMI technology is likely to converge with the inexorable improvement of computing power. Modern mobile phones have more capacity than personal computers had a decade ago. A decade from now, devices small enough to be surgically implanted in the brain could have considerable computing power, if we are to believe Moore’s law. What this convergence may produce is impossible to tell. Perhaps progress will be obstructed by an unforeseen obstacle. But internal computers that connect brains to the internet, devices that monitor neural conditions and other ideas that seem like pure fiction today may very well be fact sooner than we think.

4. Brain Imaging

Two imaging techniques that are often used to facilitate the implanting of BMIs are magnetoencephalography (MEG) and (neural) functional magnetic resonance imaging (fMRI). MEG is an imaging technique used to measure the magnetic fields produced by electrical activity in the brain via extremely sensitive devices. In research, MEG’s primary use is the measurement of time intervals of activity. MEG can resolve events with a precision of 10 milliseconds or less. MEG also accurately pinpoints sources in primary auditory, somatosensory and motor areas, but its use in creating functional maps of the brain during more complex cognitive tasks is more limited; in those cases MEG is best used in combination with fMRI.

fMRI uses a powerful magnetic field to align the nuclear magnetization of hydrogen atoms in the water in an organism. Radio frequency fields are used to systematically alter the alignment of this magnetization, causing the hydrogen nuclei to produce a rotating magnetic field detectable by the scanner. This scan detects changes in the blood flow in the brain and spinal cord. Since the early 1990s, fMRI has come to dominate the brain mapping field due to its relatively low invasiveness, absence of radiation exposure, and relatively wide availability. Another advantage is that it can map brain activity deep inside the brain, whereas MEG and EEG are biased towards its surface. It also
has the advantage of a high spatial resolution and can produce clear images of brain activity. An experimental approach seeks to integrate the information provided by a structural MRI and scalp EEG to provide a noninvasive alternative to ECoG.

Research developed in the Advanced Telecommunications Research (ATR) center in Kyoto, Japan allowed scientists to reconstruct images directly from the brain and display them on a computer. While the early results are limited to black and white images of 10×10 squares (pixels), resolution may improve significantly according to the research team. To reconstruct images from the brain is indeed impressive. But can we decode neural activity for complex purposes such as what people are thinking about? Not yet. Brain complexity is vast. Deciphering the activity of the neural network would require a multilevel recording of brain activity on all the important nodes involved in brain activity, which is not possible at the moment because of the number of deep intracerebral recordings that would be necessary. New technologies need to be developed, such as miniaturization of deep brain recording devices or more efficient extraction of deep brain activity signals from the surface.

5. Ethical considerations

The pace of the development of various BMI applications outlined in this paper justifies efforts to outline the ethical issues that may arise from the use of these applications. One issue worthy of some consideration concerns emotions of disgust that implants sometimes evoke, and the potential for social ostracism. Another concern relating to BMI and other enhancement technologies is the claim that the normalization of less controversial technology may lead to the acceptance, in the future, of more controversial technologies. This is sometimes labeled the slippery slope argument. Finally we have the argument from equality, the idea that enhancement technologies exacerbate and cement social inequalities. These issues will not be considered here. Instead I would like to focus on more pressing concerns that have not been addressed to a full extent. The following issues appear to be of particular importance: dignity, privacy and autonomy. My general outlook is that the problems these issues pose could be dealt with some regulation, rather than with outright bans of this technology. 6.

Concluding remarks

BMI technology and brain imaging has the potential to radically change many aspects of everyday life. This paper has described the various existing and experimental innovations in this field. The need for an assessment of how regulation could ensure that this technology does not violate our most cherished values is evident.

7. References

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