Editorial

Brain–Machine Interface: The future is now

Science fiction writers, particularly of the Hollywood kind, have always fantasized about fusing the power of the human brain with the strength of machines. Famous examples include the Borgs of the Star Trek, Dr Octavius of Spiderman, and Darth Vader of the Star Wars series. Most of these characters are portrayed as evil. However, what is lost in the evilness of Darth Vader is the fact that his villainous metallic appearance was due to a remarkable surgical intervention, which provided motor abilities to his burnt and dismembered body after his fight with Obi-Wan Kenobi on the volcanic planet Mustafar. Over the past decade, such restoration of function has slowly moved from the realm of science fiction to science journals. Many laboratories around the world are developing brain–machine interface (BMI) assistive devices, which can be controlled by patients with paralysis using signals from their brains. This audacious goal is becoming a reality due to a rapid increase in our understanding of the brain organization and function, a phenomenal increase in the power of small computers, and advances in humanoid robotics.

BMI technology has three components: (i) a system to detect and record signals from the brain; (ii) a signal analyser to decipher the recorded signal; and (iii) an effecter device which executes the intended action based upon the output from the signal analyser. I briefly describe each of these components, and the current state of the art in the BMI technology.

Recording signals from the brain

There are many techniques for recording electrical activity of the neurons, each with its merits and limitations. The least invasive method for recording signals from the brain uses electrodes placed on the scalp to obtain an electroencephalogram (EEG). EEG offers an advantage in that the electrodes can be easily repositioned for optimal recordings. Moreover, for testing and development, human subjects and patients can be freely used since the technique is completely non-invasive. However, the spatial resolution of EEG is low, and the information content of the signal is poor due to attenuation by the skull and the membranes. Despite these limitations, Birbaumer,[1] among the pioneers of BMI, could get patients with amyotrophic lateral sclerosis (ALS) to use cortical potentials to manipulate a communication device. Although the spatial resolution of EEG can be enhanced by increasing the number of recording electrodes, the set-up procedure remains complex and time-consuming, and requires help from another person.

The second recording technique, electrocorticogram (ECoG), uses electrodes placed on the surface of the brain, either above the dura or under it. Here the spatial resolution and the signal content are better than EEG. Although this technique has not been exploited much for the development of BMI, it remains of potential interest because it is less invasive as compared to intracortical electrodes.

The third technique involves recording from a large number of microelectrodes placed intracortically close to the neurons. These electrodes give the best spatial and temporal resolution. The recorded signals have the maximum amount of information, since both the action potentials and the low frequency local field potentials can be recorded. However, there are concerns regarding the use of intracortically implanted electrodes in patients. Long term consequences of the presence of electrodes in the cortex, in terms of adverse tissue reactions are not known. Cellular reactions such as gliosis can also change the recording characteristics of the electrodes, affecting *in vivo* longevity of the device. Therefore, development of biocompatible materials with suitable electrical characteristics remains an active area of research. We have used teflon-coated stainless steel microwires for as long as 2 years in non-human primates without significant loss of recording quality, which shows that damage to the brain is minor and it does not affect functioning of the implanted region of the brain. Electrode arrays manufactured from silicon material, popularly known as 'Utah' type of electrodes, have also been used. The current technology does not permit them to be fashioned much longer than about 1000 micrometre, which limits their use to the areas of the brain that are exposed on the surface. However, these are the only kind of electrode arrays that have been used in an approved human trial.[2] Other concerns with intracortically implanted electrodes are that they cannot be repositioned easily, and we can record from only a small region of the brain. The site for implantation, therefore, must be selected carefully.

The motor and premotor cortex have been explored as the most promising sites for implantation of electrodes. In these areas, trajectory of the forelimb, even in the three-dimensional space, can be fairly reliably predicted from the activity of a surprisingly small number (about 20) of neurons.[3] Demonstrations that the neuronal firing pattern can be tuned by training and operant conditioning,[4] mitigates some of the concerns regarding the level of precision needed to place the electrodes. An issue affecting progress in the use of intracortical electrodes for BMI is that the entire research and development has to be done in animal models, which is hard and time-consuming because animals cannot understand verbal commands, and therefore take much longer to learn to control their brain activity to generate the desired signal.

Signal analysis

While great technological advances have been made in our ability to record electrical signals from the brain, the second component of the system, signal analysis, has lagged behind. The root of the problem lies in our ignorance of the code that the brain uses for information processing and transmission. Some aspects of the sensory inputs quite reliably correlate with the frequency and timing of the action potentials of neurons. However, the relationship starts to become obscure in higher areas of the brain, and as the dimensionality of the input increases. Georgopolous *et al.*[3] demonstrated that a vector derived from the activity of a population of neurons in the motor cortex can better predict the direction of movement of the arm as compared to the activity of a single neuron. Many complex mathematical tools have since been used to help decode the activity of neuronal populations. Some of these, such as principal component analysis (PCA), have proven to be reliable under limited conditions. However, the universal code, if it exists, remains elusive. Current levels of success have been achieved by using algorithms that train neural network kind of computer programmes, which use real time feedback from the robotic device to fine-tune the interface for a better control.

The robotic device

True humanoid robotic devices are still in development. An ideal robotic device would be one that mimics a human hand in all its versatility, with a precise motor and force control based upon its internal feedback from tactile inputs. Current robotic devices, on the other hand, are usually able to perform only a limited set of tasks. Simple robotic arms have been controlled using brain signals for self-feeding in non-human primates[5,6] and even rodents.[7] A major effort has been directed towards achieving computer control, as in gaming devices, so that the computer can in turn be used to control other proximate or remote electronic devices.

Ethical considerations and the current status

A large number of artificial devices are routinely used to replace worn out, damaged or diseased body parts. Intracranial devices such as for deep brain stimulation, and electrodes arrays for locating epileptic foci are approved for medical use. However, as mentioned earlier, the idea of a brain implant strikes many as repugnant, who feel that such devices interfere with our 'innate humanness'. My own unscientific survey indicates that generally patients with a disability are more open to the use of implants as compared to healthy people. The feeling of revulsion is exacerbated by the thought of electrical wires emerging from the skin. To address this concern and to provide greater freedom to patients, technologies to transmit data wirelessly from a subcutaneous implant to a receiver are being developed. However, success has been limited so far, because the wireless device should be capable of high data throughput, while being small and lightweight, and at the same time have low power requirements.

Clinically, there have been many demonstrations of the control of external devices by humans using their brain signals, including patients with spinal cord injury, ALS and stroke.[8] The results show that a certain degree of control can be easily achieved, except for patients who were already completely locked-in. This is hypothesized to be due to a lack of any meaningful feedback loop.[8]

The use of intracortically implanted electrodes has been more extensively explored in monkeys, where the monkeys have successfully been able to feed themselves using a robotic arm.[5,6] An interesting experiment showed that it is possible to use the brain signal to electrically stimulate the muscles of the paralysed forelimb for evoking movements.[9] In humans there have been trials of the 'Utah' type intracortical electrodes implanted in the primary motor cortex of quadriplegic patients.[2] One of the patients had sustained a knife injury at C3–C4 level 3 years previously. The recordings were done for approximately 10 months. This patient could achieve fairly sophisticated cursor control. He was able to operate simple software as well as control a multi-jointed robotic arm. Although considerable signal loss was observed around 6 months after the implant was done, the impedance measurements indicated that the loss was due to non-biological reasons. Thus, BMI technology has already been successfully demonstrated, although for a limited set of tasks and in a laboratory setting. The success reflects the remarkable plastic ability of the brain, and the patient's ability to voluntarily modulate the activation pattern of neurons. With increasing efforts in laboratories around the world, BMI devices have a potential to become a viable option for patients with complete loss of motor control.

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