

Brain-Machine Interfaces



Josep Miquel Jornet¹, Michal K. Stachowiak²,
and Sasitharan Balasubramaniam³

¹Ultra-broadband Nano Communication and
Networking Laboratory, University at Buffalo,
The State University of New York, Buffalo, NY,
USA

²Department of Pathology and Anatomical
Sciences, University at Buffalo, The State
University of New York, Buffalo, NY, USA

³Telecommunication Software and Systems
Group, Waterford Institute of Technology,
Waterford, Ireland

Definition

Brain-machine interfaces (BMIs) refer to communication systems between the brain and an external device. Desired properties of BMIs include bidirectionality, high spatial and temporal resolution, low invasiveness, accuracy, and robustness. In this paper, the different types of BMIs, the state of the art, and the future directions are discussed, in addition to highlighting their key applications.

Historical Background

For many decades, the interaction between humans and machines has been restricted to the exchange of visual, auditory, and tactile infor-

mation. A conceptual analysis of the existing human-machine interfaces (HMI) reveals that the amount of useful information that can be exchanged between humans and machines is not limited by the capabilities of the human brain or those of the machine processor, but by the interfaces between them. Simply stated, from an engineering perspective, the human being can be modeled as a *macro-system* with a processing powerhouse, i.e., the brain, and a collection of peripherals, i.e., the sense organs. All the peripherals have their own latency limitations, which mainly arise from the fact that they convert a collection of *nano-/micro-events*, i.e., neuronal activity in the form of action potential signals, into a *macro-sized effect*, e.g., moving the fingers to touch a display or type some characters in order to control an external machine or, reciprocally, convert a macro-size effects, e.g., an auditive or visual command, into a collection of nano-/micro-events in the brain.

In order to overcome the limitations of the peripheral system, direct communication with the brain is needed. This form of interaction is known as a brain-machine interface (BMI). Over the years, numerous applications have resulted from these two-way interactions, where compensations are made between the computational capabilities of both systems. Such compensations can be in the form of either the computing system analyzing the brain signals and adapting the computing environment or the computing system providing added computing power to compensate for shortcomings of the brain. In the first case, brain

signals are used to understand the user's context which is then used to control machines, such as controlling the vehicle. In the second case, this could come in the form of computing systems controlling neuroprosthetic devices for disabled patients.

Electrical Brain-Machine Interfaces

The most common to date BMIs rely on the collection and excitation of electrical signals from the brain. Electroencephalogram (EEG) signals have been successfully utilized to directly control machines without the need of the sense organs (Millan et al. 2004). EEG signals can be collected in a noninvasive way, i.e., from outside the brain, and support high-temporal resolution, i.e., down to the sub-millisecond scale, but have limited spatial resolution, i.e., cannot be utilized to read the action potential signal from a single neuron at a time, and are vulnerable to electrical artifact sources. Besides EEG-based BMIs, there are other more invasive mechanisms that could be utilized to enable more robust electrical BMIs, such as intracranial EEG (Leuthardt et al. 2006), which is also known as electrocorticogram, and microelectrode arrays, which are placed directly on the exposed surface of the brain (Hochberg et al. 2006). However, besides their invasiveness, they suffer from several limitations, such as complex application or unsuitability for long-term use.

Optical Brain-Machine Interfaces

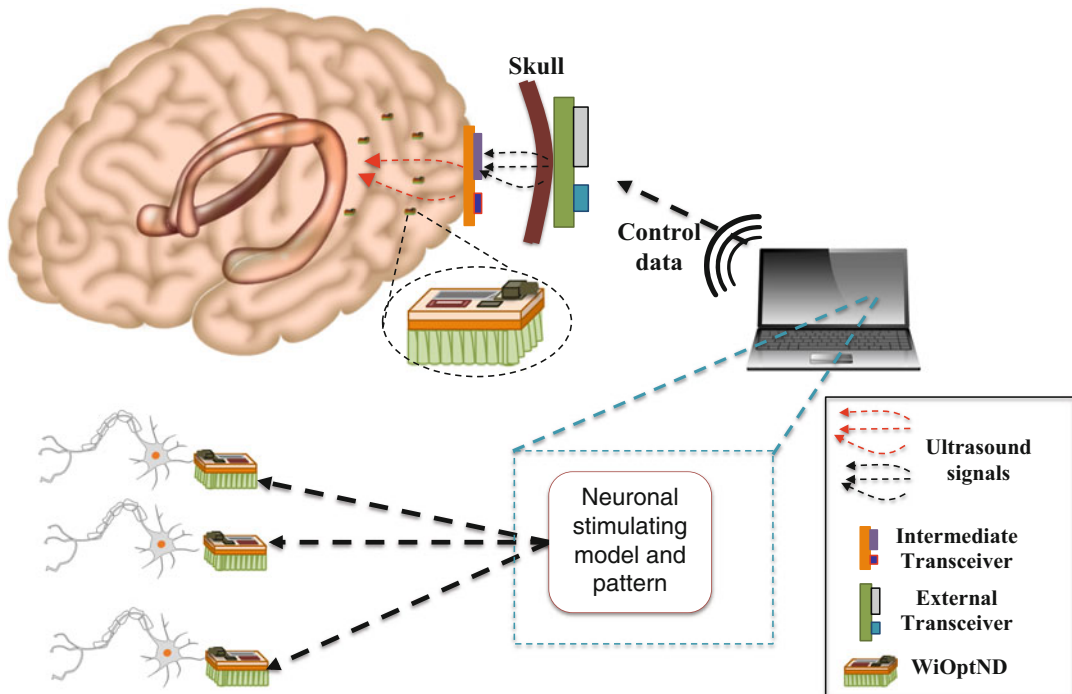
In parallel to the development of the aforementioned approaches, the field of optogenetics, i.e., the use of light to interact with genetically modified neurons in the brain (Zemelman et al. 2002; Deisseroth 2011; Zhang et al. 2007), has experienced a major revolution in the last decade. Optical neural stimulation is considered to be more beneficial than electrical neural stimulation, because it permits activation or inhibition of specific types of neurons with sub-millisecond temporal precision and eliminates electrical artifacts. Cur-

rent approaches to optogenetic neural interfaces include the use of optical fibers coupled to lasers or light-emitting diodes (LEDs) (Zorzos et al. 2010) and micro-LED arrays (McGovern et al. 2010). Moreover, optogenetics enables bidirectional interfaces, as light can be utilized both to control and to measure neuronal activity (Kwon et al. 2014). However, the size of existing optical devices makes them invasive, difficult to contact to individual neurons, and, ultimately, not suitable for chronic BMIs (Marblestone et al. 2013).

Wireless Brain-Machine Interfaces

In order to overcome the limitations of traditional electrical and optical BMIs, wireless BMIs are being developed. In Seo et al. (2013), the concept of neural dust was introduced for the first time. In the envisioned architecture, miniature electronic devices or dust motes are implanted in the cortex. These devices, which integrate piezoelectric energy harvesting systems powered by ultrasounds, record the neural activity from the cortex and transmit the information to a subdural transceiver mounted under the skull. This device is in charge of controlling the neural dust and to communicate with the external head-mounted transceiver, where the data is collected. Despite the advantages of this wireless architecture, the fact that it relies on the principles of electrical BMIs limits its applications.

Recently, in Wirdatmadja et al. (2017), the first wireless BMI based on wireless optogenetic nanonetworking devices (WiOptNDs) was proposed (Fig. 1). WiOptND enables accurate, robust, high-throughput, and minimally invasive BMIs by leveraging the state of the art in nanophotonics, nanoelectronics, and wireless communication. The fundamental idea is to replace existing micro-LED arrays and micro-photodetector arrays used in optical BMIs by a network of coordinated nano-devices, which are able both to excite individual neurons and to measure their activity. In this application, a network of collaborative WiOptNDs is utilized both to excite multiple neurons according to



Brain-Machine Interfaces, Fig. 1 The WiOptND architecture consists of (i) a network of coordinated nano-devices able to optogenetically excite and measure the response of neurons; (ii) an intermediate transceiver in charge of both controlling the nano-devices in order

to generate different neuron excitation patterns as well as acoustically powering them; and (iii) an external transceiver in charge of acoustically powering the intermediate transceiver and interfacing it with the actual BMI user

incoming commands and to collect, process, and transmit accurate neuronal activity in real time. Each nano-device is equipped with an optical nano-transceiver (Feng et al. 2014) and nano-antenna (Nafari and Jornet 2017), which is able to both emit and detect optical radiation at a pre-established frequency or wavelength. As in Seo et al. (2013), WiOptNDs are acoustically powered and remotely controlled through the subdural transceiver (Fig. 1).

Many benefits in this approach exist. First, the very small size of optical nano-antennas (Dorf-muller et al. 2010; Nafari and Jornet 2017), below 1 micrometer in the largest dimension, enables the possibility to measure the neuronal activity in a single neuron, with very high accuracy. Moreover, the total size of each individual nano-device, up to a few cubic micrometers at most (Akyildiz and Jornet 2010), minimizes the

invasiveness of this approach when compared to existing optogenetic approaches, which require bulky lasers or optical fibers. Moreover, by operating at optical frequencies, much higher temporal resolution than traditional electrical BMIs can be achieved. For example, while the main features of action potential signals are in the millisecond scale, the possibility to measure those signals with much higher temporal resolution, such as a few microseconds or even less, may unveil new high-frequency time transients in the action potential signal propagation, which could shine new light into the exploration of neuronal pathways. This also enables potentially much faster BMIs. For the time being, however, electrical and optogenetic BMIs are at an early stage, in which some of the system components have been developed and tested, but a fully functional BMI has not been realized.

Future Directions

To enable practical long-term implantable wireless BMIs, there are several bottlenecks that need to be overcome.

- From the *hardware perspective*, the major challenges are in terms of the miniaturization of the neural dust motes. Nano-lasers, nano-antennas, and nano-photodetectors are needed to excite and monitor neural activity through optogenetics. For the time being, the smallest laser, experimentally demonstrated to date (Feng et al. 2014), is a micro-ring laser with 10 μm in diameter. Given the average size of a neuron cell body, tens of micrometers, current nano-lasers should be able to achieve single neuron resolution, provided that they are near it (otherwise, light spreading would result into the illumination of multiple neurons). Optical nano-antennas can be utilized to then overcome this problem. Besides the optics, piezoelectric energy harvesting nano-systems (Wang 2008; Wang et al. 2017) and minimal computational and data storage capabilities are needed.
- From the *communications perspective*, effective communication protocols to operate the WiOptNDs are needed. Addressing of individual nano-devices, precise triggering of the optical stimulation, and accurate collection of information are crucial tasks to be performed reliably and with energy efficiency in mind. When developing such protocols, the physics of the intra-body channel, which affects the propagation of optical signals for optogenetic excitation and measurement (Wirdatmadja et al. 2018) as well as of the acoustic signals required to power the nano-devices (Donohoe et al. 2016), need to be taken into account. As important as their impact on the signal power, their impact on time distortion and synchronization needs to be studied (Noel et al. 2018).
- In all cases, *human factors* need to be taken into account. For the time being, the advanced BMIs (i.e., anything beyond EEG signal col-

lection from over the skull) have been primarily tested in vitro cell cultures or animals. One of the promising approaches relies on the use of cerebral organoids, i.e., artificially grown, in vitro, miniature organs resembling the brain. These organoids reproduce the exact behavior of the brain and are the basis of recent breakthroughs in neuroscience (Stachowiak et al. 2017). Beyond in vitro testing, the implantation of the devices needs to be optimized. Beyond surgery, the combination of nasal injection and self-assembly techniques for nano-devices is being considered.

Key Applications

- BMIs can significantly improve the quality of life of people with disabilities, by providing them a transformative way to interact with the environment and restoring functional abilities and even cognition. For example, the direct control of machines from the brain can help to overcome the limitations in the “interfaces” between them, namely, the sensor organs or locomotion apparatus.
- BMIs can help to broaden the understanding of the developmental- and aging-related diseases, such as schizophrenia or Alzheimer, whose origin lies at communication problems between consecutive neurons, and, ultimately, enable transformative treatments.
- BMIs can help to control specific types of neurological disorders, which to date have been a major challenge. A good example is epilepsy. The development toward using miniaturized neural dust motes that can be implanted deep into the brain, coupled with optogenetics, can provide a mechanism of controlling neurons at a single cell level. This means that by understanding the source of the epilepsy, controls can be developed to suppress the seizure signaling.
- BMIs can help to augment people’s brain power going into the future. New concepts such as *Targeted Neuroplasticity Training* can

emerge, whereby the computing power capabilities are augmented with the brain's training process. This could enhance the brain with new skills and also provide people the abilities to acquire new skills where they previously lacked.

Cross-References

- [Nanonetworks](#)
- [Nanoscale Terahertz Communications](#)
- [Terahertz-band nano-communications](#)

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