Editorial: Developing the Next Generation of Hybrid Neuroprosthetic Systems

In the 1950s, E. Von Gierke stated that the goal of bionics is "to extend human physical and intellectual capabilities by prosthetic devices in the most general sense" [1]. In the past, many groups have been working on the development of bionic (or hybrid neuroprosthetic) systems [2], [3]. These devices can be used to restore functions in people affected by spinal cord injury, traumatic brain injury, or amputation. In the last case, the natural limb is not available and a link between the nervous system (NS) and the artificial limb must be created. In the other cases, the natural limb is still "available" but the connection between different parts of the NS is compromised.

The hybrid neuroprosthetic system (HNPS) is emerging as one of the most innovative areas of robotics and biomedical engineering. HNPSs may assume a variety of forms and configurations. Three key attributes proposed for a general classification of HNPSs are given in Fig. 1 [4], [5].

— *Level of Hybridness (H):* ranging from separate artificial and natural systems (H0), to exoskeletons copying the mechanical properties of natural limbs (H1), up to artificial body parts anatomically and functionally "connected" to the human body (H2).

— *Level of Augmentation (A):* empowering sensing, perception, and motor capabilities. The level of augmentation increases along with the number and type (perceptual or/and motor) of empowered capabilities

— *Level of Connection to the Nervous System (C):* modality by which the artificial and natural systems are connected. To this aim different solutions varying from multimodal indirect interfaces to direct interfaces to the peripheral nervous system (PNS), or to the central nervous system (CNS) can be used.

The basic scientific and technological challenges related to the development of different HNPSs can be addressed by taking direct advantage of the concepts and knowledge already developed within different areas of Neuroscience, such as the understanding of motor control strategies implemented by the CNS (cortical areas, basal ganglia, brain stem, cerebellum, and dedicated spinal cord circuits) or the sensory processing leading up to perception with specific reference to visual and haptic sensing.

As for direct interfaces to the NS, it is possible to focus onto novel interfaces implanted at the PNS level (cuff [6], [7], intraneural [8], [9], or regeneration types [10]), and onto invasive [11]–[18] and noninvasive [19]–[26] interfaces (such as MEG, EEG, (f)MRI) at the CNS level. For example, new technologies for online processing of EEG data and recording of brain activity in active humans can be exploited. In HNPSs, the brain is always in charge of the overall control and coordination of the hybrid bionic system. It could be interesting in the future to verify whether it is possible to develop HNPSs able to evolve and adapt in order to deal with unexpected and unplanned real-life situations. To this aim it is very important to deliver rich, almost natural, sensory feedback that will provide the artificial algorithms and the user's nervous system with the correct data to help develop a hybrid cognitive model of the interaction with the environment.

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This kind of "concurrent hybrid understanding" between the nervous system and the artificial components could allow the HNPSs to respond intelligently to situations and events that have not been specified during the design phase. In this way the HNPSs will be able to evolve, increasing its effectiveness in real-world conditions and becoming more adaptive (to changing tasks and situations), more robust (against perturbations), more effective (learning from the past to anticipate or predict the future), and more natural (becoming a new part of the body of the user). Presumably, this will be possible only if the HNPS is able to receive and process correctly many concurrent sources of sensory information about the task and about the environment. Thus, the restoration of sensory pathways will be crucial for the evolution of HNPSs.

Special Issue on Hybrid Neuroprosthetic Systems

Here, we would like to present a special issue on Hybrid Neuroprosthetic Systems to the IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING readership with the goal to provide more information about leading research activities carried out by groups around the world working to develop more effective HNPSs. Some of these papers were submitted in response to our call for HNPS papers, while others were submitted as part of the regular publication process of TBME.

The collection is divided into three main areas dealing with the some of the most important aspects related to the development of HNPSs:

Electrodes and interface technology: Wang and colleagues addressed the issue of developing more effective flexible substrate electrodes. In particular, the combination of sputtered iridium oxide films together with liquid crystal polymers has been tested with very promising results. Venkatraman and colleagues showed the results related to the development of a system for closed-loop microstimulation in awake rodents chronically implanted with multielectrode arrays. Intracortical stimulation can be used as a means of providing the user with sensory feedback. Hsu and colleagues tested the efficacy of a new hermetic encapsulation of an integrated neural interface. This is a crucial issue to develop chronically usable interfaces. Thorp and colleagues analyzed the relative importance of different interference sources during intracranial microwire recordings. This kind of studies is very important to improve the signal-to-noise ratio during neurophysiological recordings. Balachandran and colleagues tested the efficacy of a new

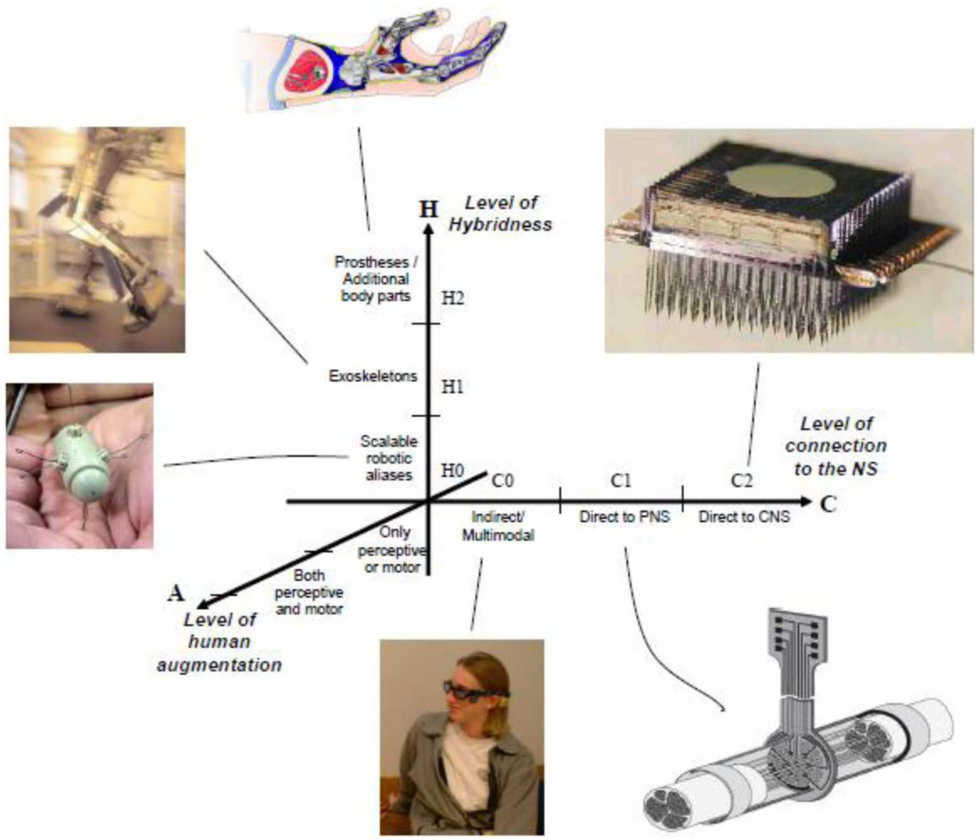

Fig. 1. Examples of different systems with different levels of Hybridness, Augmentation, and Connection [4], [5].

approach for the placement of the electrodes for Deep Brain Stimulation. This approach is based on the use of "virtual targets", which eliminates the problem of collision of the implant with the target. Sharp and colleagues developed a model of the micrometer scale penetration mechanics and material properties of mouse brain tissue in vivo. The understanding of this issue is extremely important to develop effective but less invasive interfaces.

Neural Signal Processing and Modeling: DiGiovanna and colleagues developed and tested in animal models a new approach to increase the learning ability in the HNPSs. It is based on a reinforcement learning paradigm and could address some of the problems related to the use supervised learning with final users. Huang and colleagues developed and tested a new a new phase-dependent pattern recognition strategy to identify locomotion modes by processing EMG signals. This approach could be used in the future to develop neural controlled artificial legs. Sieluzycki and colleagues showed the results of the use of an innovative algorithm for the analysis of brain evoked electromagnetic potentials and fields. This approach could significantly increase our understanding of these signals. Li and colleagues developed a new approach for the estimation of single-trial ERP based on an innovative filtering technique. This method is characterized by a high flexibility being able to change the shape and scale parameters continuously.

Lin and colleagues used a new radial basis function network based on higher order statistics for the analysis of ERP. This new approach is able to overcome some of the problems affecting other existing solutions. Wang and colleagues developed a new method to combine neuronal signals from multiple electrodes to maximize the predictive performance of ROC analysis. This new approach is based on the use a distribution-free relaxation based multichannel signal combination and it is shown to provide quite promising results. Xu and colleagues an innovative method for estimating event-related potentials on a trial-by-trial basis. This approach was also tested with experimental data recorded in vivo showing that it can help gathering useful physiological information. Barton and colleagues used a Kalman filter for EEG Source Localization with interesting and promising results. Liu and colleagues analyzed the role of slow potassium current in nerve conduction block induced by high-frequency biphasic electrical current. Their simulations studies were able to provide interesting physiological findings. Tan and colleague developed a mixture separation model for the detection of multifiber neuronal firings in sympathetic recordings. This new approach significantly outperformed the traditional processing methods.

Prosthetic Devices: Weir and colleagues presented a new implantable microsensor to record EMG signals. This device could be used in the future to develop neural controlled artificial limbs. Pezaris and Reid carried out simulation experiments about the development of a thalamic visual prosthesis. They addressed several important questions about the characteristics the electrodes should have to make this approach more effective. Lujan and Crago developed an innovative approach for the design of feedforward control algorithms for motor neural prostheses. The results achieved confirmed that potentials of this method both with able-bodied and disabled people. This approach can be used to increase the usability of hand prostheses while handling delicate objects. Choi and colleagues developed a human-machine interface based on the processing of EMG signals. For its simplicity it could be used in the future by severly disabled subjects.

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SILVESTRO MICERA, *Guest Editor*
Advanced Robotics Technology
and Systems Lab
Scuola Superiore Sant'Anna
Pisa, 56127 Italy

Institute for Automation
Swiss Federal Institute of Technology
Zurich (ETHZ)
Zurich, CH-8092 Switzerland

JOSE M. CARMENA, *Guest Editor*
Department of Electrical Engineering
& Computer Sciences
University of California
Berkeley, CA 94720 USA

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