Co-Evolution of Human and Machine: Neuroprosthetics in the 21st Century

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Abstract— **Throughout the history of mankind, tools have served the role as passive extensions of the body. Recently, the development of neuroprosthesis has changed the scope of how humans interact with tools. Neuroprosthetics enable direct interfacing with the brain and have the great potential for restoring communication and control in disabled individuals. The transformative aspect of direct neural interfaces is that they can be designed as 'intelligent tools' that not only carry out intent but also have the capability to assist, evolve, and grow with the user. Unlike other tools, neuroprosthetics exist in a shared space that seamlessly spans the user's internal representation of the world and the physical environment enabling a much deeper human-tool symbiosis. Recent advancements in the engineering of neuroprosthetics are providing a blueprint for how new co-adaptive designs change the nature of a user's ability to accomplish tasks that were not possible using conventional methodologies. This paper analyzes how key advances in science and technology supporting the development of intelligent neuroprosthesis and contrasts them with "lessons learned" from the past 50 years in the IEEE.**

Keywords-neuroprosthesis; brain-computer symbiosis; cybernetics; brain-machine interface; co-adaptation

I. Introduction

The great promise of neuroprosthesis is that they can be used to develop communication pathways directly between the brain and external devices to restore and augment sensory, motor, and reward neural function [1]. For many disabled individuals, the concept of using an electronic device to bypass injury or aid in rehabilitation is liberating because the prosthetic system can restore lost communication or control function [2]. Neuroprosthetics present many "grand challenges" for electrical, biomedical, and neural engineers because they are in direct contact with the body's command and control systems. Therefore, system design must accommodate the seamless intertwining of biological systems of neurons with electronics, mechanics, and materials [3]. The basic building blocks of a neuroprosthsis system are presented in Fig. 1 and consist of sensing neuronal activity (on the order of microvolts), transmitting this information out of the brain, decoding its information content with signal analysis, and providing feedback through control. In addition to these elements, the design challenge is heightened with the goal to create systems with an element of biomimicry or the ability to closely replicate physiological function [4].

While the concept of neuroprosthesis may seem futuristic, there are several inspiring examples of the technology in clinical practice today that have demonstrated feasibility and even therapy. The best known of these examples are the deep brain stimulators or DBS. These devices fall into a category with the goal is to primarily send signals into the brain (as opposed to read out information) to treat the symptoms of Parkinson's disease, tremor, and dystonia [5]. While the majority of DBS system design in the past has been "open loop", there are new efforts to build "closed loop" devices that are responsive to changes in sensed brain activity [6]. The idea of using "closed-loop" systems was primarily derived from the great progress in a second class of neuroprosthesis that seek overcome paralysis by bypassing spinal cord injury using the neural interface to control prosthetic limbs directly with brain activity [7-9]. Landmark experiments in rats, monkeys, and humans have shown that with well engineered systems that acquire neural activity [10], translate it through signal processing algorithms [11], and deliver the appropriate prosthetic or computer commands [12, 13] that direct brain control can be achieved without physical movement. While these proof-of-concept experiments demonstrate the feasibility of motor neuroprosthesis in relatively simple tasks there is a vision among neuroprosthesis researchers that these devices should be used in complex activities of daily life. If this vision is delivered, then the neuroprosthesis will likely move beyond a simple extension of the body and play more of an assistive role in the user's life because it is intimately interfaced with the nervous system and participates in goal-directed tasks. The idea of sharing control between the user and machine has deep roots in the history of the IEEE. The foundations of these concepts will be discussed here

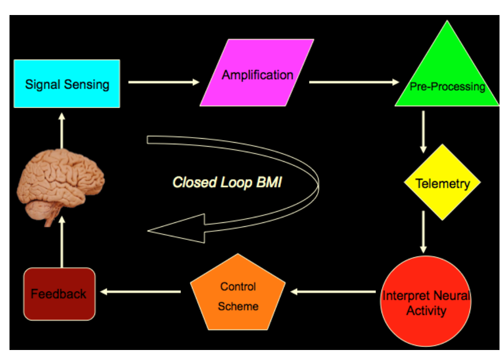

Figure 1. Basic building blocks of a neuroprosthetic system.

II. Elvolving History of Human-Tool Interaction

Since the even the earliest phases of human history, the use of tools has had a profound impact on life. While tools have been great enablers to improving quality of life, they have primarily served in a passive role. Commands are given and outcomes are expressed through the tool. Although passive, tool use has been very unique in our development as a species because they can extend the body schema (through extending the natural reaching space) and induce plastic changes in neural system representation [14-16]. This property has given tools an evolving role in human life. In the early 1940s, a significant transformation in the role of tools was brought out during World War II. This period marked the beginning of goal-seeking machine behavior through the development of anti-aircraft gun control [17]. The key change in the rationale behind design in this application is that the tool (gun) did not participate passively with the user. It sensed the environment and through feedback reacted to the information gathered. After the war, scientists and engineers realized the power of this new concept begin to apply wartime techniques to a broader set of problems. The approaches to automatic control were enhanced with principles derived from living organisms, human society, and communication theory with a focus on information, feedback, and control.

From 1946-1953 a series of conferences sponsored by the Josiah Macy foundation further helped to lay the foundation for the evolution of tool use. There was a great push to bridge the hard and soft sciences through the linking of biological phenomena, anthropology, engineering, mathematics, and computing. Key members at these meeting who have played instrumental roles in the IEEE include Shannon [18], Weiner, Meade, Von Neumann [19], McCulloch and Pitts [20]. One of the primary outcomes of these meetings was the maturation of the field of Cybernetics [21]. It introduced the concept that tool performance could be improved with control systems that have humans in the loop. System designs were considered with goals in mind and using circular feedback loops of sensing, comparing with goals, action, sensing, etc. This cyclic phenomenon naturally lead to pursuit of the understanding of human-to-computer interaction. In 1960, Licklider postulated the idea of man-computer symbiosis [22]. He sought to revolutionize information handling by tightly coupling humans and computing machines engaged in a "partnership" and "dialogue." What is quite remarkable about these meetings is that they provide many of the principles used in neuroprosthetic control (closed-loop, feedback, tight coupling of human and machine) however these forefathers would likely not have ever considered their use in neural interface applications.

III. Impact of Neural Information Processing

While many of the advances in control theory were occurring, others were interested in translating thoughts into action though understanding the neural code [23] and how stimuli activates neural responses. The theory of neural information processing begins with the neuron doctrine and Santiago Ramon y Cajal but was really lead by Cajal's last graduate student Rafael Lorente de No in his study of the mechanisms of neural substrates of physiological function. Much of this work inspired the development of many of the tools that are currently used in neuroprosthetic design including perceptrons [24], neural networks [20], supervised [25], semisupervised [26], and unsupervised learning [27]. Researchers working in this area have recognized the power of these techniques and neuroprosthetic decoding theory has been driven by adaptive signal processing. Supervised and unsupervised learning with input-output models have been the key players in neuroprosthetic design [11].

The culmination of all of this work (both neural and computational) forms the cornerstones of neuroprosthetic design and includes the following:

- Neural Information Processing
- Adaptive Signal Processing
- Feedback Control

IV. Lessons Learnd and Vision for Next Generation Brain-Machine Interaction

While this brief history of the fundamental principles that provide the substrate of neuroprosthetic design may lead one to believe that the primary challenges have been solved, it is quite ironic that the relationship between the user and neuroprosthetic is inherently lopsided. The full realization of active tools over passive tools has not been achieved. It is quite remarkable that even though users are intelligent and can use dynamic brain organization and specialization, neuroprosthetics are still being designed as passive devices that enact commands. Moreover, even with what is known about feedback control systems (as was posed in the 1940s) neuroprosthetics are primarily input-output models that have difficulty contending with new environments without retraining.

This naturally poses the question, "What is the vision for the next generation of neuroprosthetics?" It could be argued that the current fundamental premise behind neuroprosthetic design does not fully embrace the intricacies of biological and engineered systems as was discussed in the Josiah Macy meetings. Perhaps, neuroprosthetics should be built on the principle that intelligent behavior arises from the action of an individual seeking to maximize received reward in a complex and changing world. With this premise, engineered systems could be designed to access the perception-action-reward cycle [28]. (Fig. 2) and be involved in the continuous process of using sensory information to guide a series of goal-directed actions.

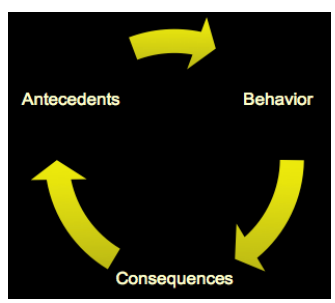

Figure 2. Cyclic nature of the Perception-Action-Reward Cycle

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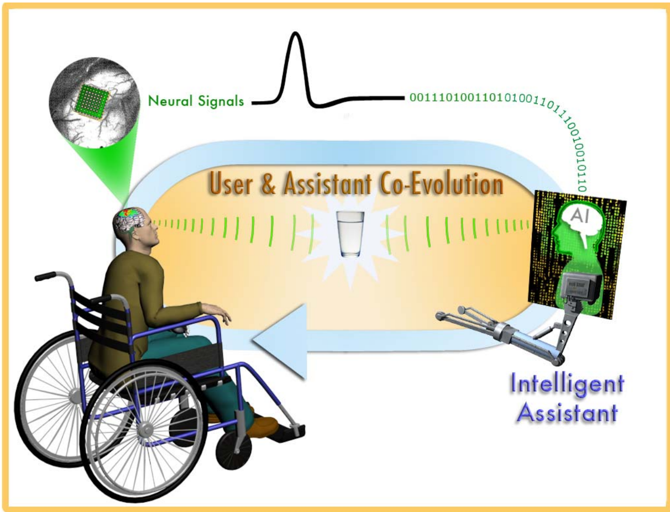

Figure 3. Symbiotic neuroprosthetic system.

A conceptual drawing of a next-generation neuroprosthetic system is presented in Fig. 3. This perspective takes the concept of Licklider and Weiner to a whole new level through the development an emergent system where the user and computer cooperatively seek to maximize goals while interacting with a complex, dynamical environment. Both the user and the computer are in a symbiotic relationship where they solve tasks in an assistive manner. This behavior depends on a series of events or elemental procedures that promote specific brain or behavioral syntax, feedback, and repetition over time [29]; hence, the sequential evaluative process is always ongoing, adheres to strict timing and cooperative processes. With these processes, intelligent motor control and more importantly goal-directed behavior can be built with closed-loop mechanisms which continuously adapt internal and external antecedents of the world, express intent though behavior in the environment, and evaluate the consequences of those behaviors to promote learning. This form of adaptive behavior relies on continuous processing of sensory information that is used to guide a series of goal-directed actions. Most importantly, the entire process is regulated by external environmental and internal neurofeedback, which is used to guide the adaptation of computation and behavior. Preliminary studies on the feasibility of this architecture have already begun to prove that it is transformative in its performance and impact on neural control of dynamic environments [12, 30].

V. Conclusions

One of the wonderful aspects of the IEEE History Society is that it facilitates evaluation of the past to help to innovate in the future. One particular message to be taken from the history of neuroprosthesis is that future societies should seek to develop a multidisciplinary culture focused on solving “grand challenges” of humanity. If there is ever a lesson to be learned from the outcome of WWII science and the Josiah Macy meetings is that scientists had a vested interest to discuss the great unknowns of biology and engineering and looked upon each other to contribute the necessary knowledge and cross-fertilized innovation to overcome seemingly insurmountable barriers. This culture of deep thinking and discussion is often lost in current academic study with hyper focus on immediate challenges instead of transformative science. One of the roles of the IEEE as a society should be to help facilitate a reconnection with our roots.

With these grand challenges in the right perspective, the IEEE can also play a significant role in the development of new technologies and tools that will be instrumental in providing the building blocks to the solution. In the case of neuroprosthesis this takes the form of the design of implantable medical devices (amplifiers, wireless, DSP, etc.). Innovation in miniaturization and overcoming power and bandwidth constraints will be critical for the future.

Finally, innovations in the future of human-tool interfaces have the potential to transform the way users interact with computers and appliances. By sharing goals, tools can become assistants to the user and facilitate the accomplishment of the task in a way that is more responsive needs of their users. There are still many scientific challenges to be addressed to make theses systems broaden the way users interact with the world.

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