Preface

This book has its origins in a meeting entitled "Toward Replacement Parts for the Brain: Intracranial Implantation of Hardware Models of Neural Circuitry," that took place in Washington, D.C., in August 1999. The meeting was sponsored by the National Institute of Mental Health (NIMH), the University of Southern California (USC) Alfred E. Mann Institute for Biomedical Engineering, and the USC Center for Neural Engineering. The motivation for the meeting was a growing realization among neuroscientists, engineers, and medical researchers that our society was on the threshold of a new era in the field of neural prosthetics; namely, that in the near future it would be possible to mathematically model the functional properties of different regions or subregions of the brain, design and fabricate microchips incorporating those models, and create neuron/silicon interfaces to integrate microchips and brain functions. In this manner, our rapidly increasing understanding of the computational and cognitive properties of the brain could work synergistically with the continuing scientific and technological revolutions in biomedical, computer, and electrical engineering to realize a new generation of implantable devices that could bidirectionally communicate with the brain to restore sensory, motor, or cognitive functions lost through damage or disease.

Recognizing the ambitious nature of such a vision, the goal of the meeting and thus of this book, was to explore various dimensions of the problem of using biomimetic devices as neural prostheses to replace the loss of central brain regions. The first two chapters focus on advances in developing sensory system prostheses. The remarkable success in development and clinical application of the cochlear implant, and the rapid progress being made in developing retinal and visual prostheses, provide the best foundation for considering the extension of neural prostheses to central brain regions.

Cortical brain areas in particular present their own set of challenges. Beyond the issues of designing multisite electrode arrays for the complex geometry and cytoarchitecture of cortical brain (chapters 3 and 12) it is clear that neural representations of sensory receptive fields are not static, but in fact are dynamic, changing over time and with experience (chapter 4). The limitations of using static, multisite electrode arrays to extract information from a dynamically changing population of neurons must be taken into account when designing neural prosthetic systems triggered by sensory ensemble codes. Sophisticated analyses of multielectrode recordings from the hippocampus in behaving animals (chapters 5 and 6) emphasize the complexity of neural representations typical of memory systems in the brain. Hippocampal neurons respond to multiple dimensions (modalities) of a given learning and memory task, with key, higher-level features distributed across populations of spatially disparate cells. How to extract information from systems with such complex functional properties in real time, process that information, and then transmit the processed output back to other parts of the brain to influence cognitive function and behavior constitutes a considerable challenge.

Given the multiple levels of function that characterize the nervous system (i.e., molecular, cellular, network, or system), chapter 7 provides one of the few existing theoretical frameworks for modeling the hierarchical organization of neural systems. Chapter 8 offers some practical approaches for how to organize multidimensional time series data to achieve representational schemes for sensorimotor coupling.

Despite these complexities, considerable progress is being made in implementing biologically realistic neural system models in hardware. The importance of this step is that, to design and construct a neural prosthetic system that can interact with the brain, the mathematical models required to capture the nonlinear dynamics and nonstationarity of neural functions need to be miniaturized for implantation in the brain or on the skull, and need to take advantage of the parallel processing and high-speed computation offered by microelectronic and optoelectronic technologies. Examples of such first steps in very large-scale integration (VLSI) are described here for the hippocampus (chapter 12) and thalamocortical systems (chapter 13). In addition, the use of photonics and holographic technologies for achieving high-density connectivity between neural processors (chapter 14) and multiple-pattern storage for context-dependent connectivities and functions (chapter 15) offer novel and exciting possibilities for achieving the complexity of neural system functions in hardware. Chapter 16 offers a series of intriguing insights on the potential synergy between neuroscience and computer engineering; that is, how the capabilities of current VLSI and photonic technologies can facilitate the implementation of biologically based models of neural systems, and how our increasing understanding of neural organization and function can inspire next-generation computational engines.

Finally, designing and controlling the interface between neurons and silicon is a critical consideration in the development of central brain neural prostheses. Communication between biotic and abiotic systems must be bidirectional, so that the "state" of a neural system "upstream" from a damaged brain region can be sampled (e.g., electrophysiologically recorded) and processed by a biomimetic computational device, with the processed output then used to “drive” or alter (e.g., electrophysiologically stimulate) the state of a neural system “downstream” from the damaged region. Moreover, the “sampling” and “driving” functions must be achieved through an interface having sufficient density of interconnection with the target tissues, and correspondance with their cytoarchitecture (see chapter 12), to maintain the requisite input-output neural representations required to support a given level of cognitive function.

Perhaps most important, the neuron/silicon contacts must be target specific and maintained for multiyear durations to justify the surgical procedures required for implantation. Three chapters (9, 10, and 11) describe some of the latest updates in designing neuron/silicon interfaces and offer insights into the state-of-the-art problems and solutions for this aspect of implantable biomimetic systems.

There were other aspects of the global problem of how to achieve the collective vision of implantable biomimetic neural prostheses that were covered at the original meeting but, unfortunately, they are not readily compatible with a written volume. For example, we considered the need for new graduate education programs to provide next-generation neuroscientists and engineers with the expertise required to address in the scientific, technological, and medical issues involved, and discussed the technology transfer and commercialization obstacles to realizing a viable medical device based on an interdisciplinary science and technology foundation for implantable neural prostheses.