EURASIP Journal on Applied Signal Processing 2003:7, 617–619

Editorial

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Neuromorphic engineering is a novel direction in Bioengineering that is based on the design and fabrication of artificial neural systems, such as vision chips, head-eye systems, auditory processors, and autonomous robots, whose physical architecture and design principles are based on those of biological nervous systems. The understanding of the brain and the application of that knowledge for health and technology will be one of the major research activities of the 21st century.

Neuromorphic engineering applies principles found in biological organisms to perform tasks that biological systems execute seemingly without effort, but which have been proven difficult to solve using traditional engineering techniques. These problems include visual navigation, auditory localization, olfaction, recognition, compliant limb control, and locomotion. The principles that biological organisms employ are still under investigation. For this reason, neuromorphic engineering is closely related to biological research, especially research in computational neuroscience. Neuromorphic engineering contributes to our understanding of biological systems by formulating and testing hypotheses of biological organization in fully functional synthetic systems. The aim of this research is to build a new generation of intelligent systems that interact with the real world much as animals do. The possible intellectual rewards and practical applications of this research are obviously very significant.

To some extent, "Bionics," popular in the 1960s, can be seen as a precursor to neuromorphic engineering. It emphasized the solutions that biology had found for a host of practical problems, and proposed to emulate those solutions. At the time, the focus was on biological materials, such as skin and muscles, rather than on trying to understand the detailed computational architecture and the algorithms used by the brain. Bionics disappeared from view, primarily due to a lack of detailed knowledge about biological systems and the lack of a suitable technology to implement biological strategies.

In the early 1980s, Carver Mead at Caltech, a pioneer of very large scale integrated (VLSI) circuit design, started to think about how integrated circuits could be used to emulate and understand neurobiology. What was different to the previous attempts was firstly, the tremendous growth in our knowledge of the nervous system and secondly, the existence of a mature electronics industry that could reliably and cheaply integrate a few million transistors and related structures onto a square centimeter of silicon. Indeed, the width of elementary features on a state-of-the-art very large scale integrated (VLSI) circuit is now entering the 100-nanometer domain, comparable to the average diameter of a cortical axon.

Although we are now able to integrate a few hundred million transistors on a single piece of silicon, our ideas of how to use these transistors have changed very little from the time when John von Neumann first proposed the architecture for the programmable serial computer. The serial machine was designed at a time when digital switching elements were large and fragile. Memory was also problematic and was stored by material unrelated to the computational devices. These constraints were consistent with a computer architecture based on a single active processor and a physically distant memory store. The constraints under which the serial machine was developed are no longer entirely relevant. On the contrary, the assumptions implicit in the traditional digital computational paradigm may now be limiting the computational power of integrated circuit technology.

A primary feature of the majority of integrated circuits is the representation of numbers as binary digits. Binary digits are useful because it is not difficult to standardize the performance of transistors, which are physical analog devices, to the extent that their state can be reliably determined to a single bit of accuracy. Analog computing is potentially more dense, because a single electrical node can represent multiple bits of information. Of course, analog computation is old news to engineers of the 1940s and 1950s. At that time, digital computers, where still too cumbersome to be used for many practical problems and engineers, resorted to analog computers that occupied entire rooms. However, once the digital computer became easy to reprogram and reasonably fast and small, it replaced analog technology. Today analog computers represent, for the main part, lab curiosities.

Analog computing is difficult because the physics of the material used to construct the machine plays an important role in the solution of the problem. It is difficult to control the physical properties of micrometer-sized devices such that their analog characteristics are well matched. The matching of analog device characteristics is the major difficulty facing an analog designer, and digital machines have an advantage over analog ones when high precision is required. Nevertheless, it is surprising that the high precision computation possible with modern computing is necessary to deal with real-world tasks in which the precision of the measurement of the data is often only a few bits. At the end of his life, von Neumann wrote a fascinating book, entitled *The Computer and the Brain*, in which he points out that the precision of the modern digital computer is entirely mismatched to the precision of the data, but it is necessary because errors in representation may multiply at each stage of the computation. In a digital computer, every bit of every number of the computation is fully restored and numbers are represented to many bits of accuracy to prevent the growth of error as the computation proceeds. The brain, in contrast, seems to use an analog representation with restoration at the action-potential output of the neuron. A typical active neuron firing rate is less than 100 spikes/second, so a neuron only has very few bits of precision. Nevertheless, they compute accurately enough for a wide range of computationally intensive sensorimotor tasks. One of the mysteries that neuromorphic engineering is trying to solve is how biological systems can compute so exactly using low precision components. The key appears to lie in the circuit architectures of neural systems, which aggregate information over a broad area and use feedback to provide an adaptation signal to all of the components of the system.

Although we do not fully understand the detailed circuits of neurobiological systems, their gross parallel architecture is clearly different from the serial computer architecture established by von Neumann. Serial computation remains the dominant form in digital computers because it executes tasks in a well-specified order and regularizes the problem of organization and communication. Parallel computers have been built, but have not gained widespread use due to the difficulty of programming them. Fine-grained parallel systems present nearly intractable problems for state-of-the-art engineering. Complex systems in which many processes interact are virtually designed using a trail-and-error method. For example, the boot sequence for a certain well-known modern aircraft is not a reproducible event; it is empirically determined that it will be complete sometime within fifteen minutes of initiation! Although they are not presently widely used, parallel systems have advantages over serial ones. Parallel systems have distributed local control and memory and can be faster and more fault tolerant than serial systems. Fault tolerance is important for integrated circuits because the number of transistors that can be integrated on a single silicon surface is limited by errors in manufacture that introduce flaws in the circuitry. Since digital computation demands perfect performance from every element in the system, chips with flaws cannot be used and wafer-scale integration, while physically achievable, is not practical for serial digital machines. Local memory and processing minimizes the amount of communication but requires that the task is to be organized in accordance with the machine architecture.

With the recognition that neurobiology has solved many difficult computational and sensorimotor control problems, it is believed that we can improve our technology by directly learning from biology. Yet, learning from biology brings problems of its own. In particular, the detailed forms of the biological solutions are difficult to analyze. An important reason for this is that the complexity of neuronal processing, particularly as it relates to system organization and function, is essentially nonlinear and so requires special methods of explanation that go beyond simple description and dissection. One successful method of explaining system function is to synthesize working models that integrate well-understood subelements into functional units. Such models attempt to characterize the operation of the brain at various levels, from synapses through behaving systems. Some of these models simply provide a compact ordering of our knowledge about a particular problem by detailed simulations. Others abstract the computational principles used by the neurons, and so are often framed within an engineering and physics paradigm.

This special issue of EURASIP JASP contains some examples of models representing the current state of neuromorphic signal processing. The issue starts with a low-level look at implementing neurons and synapses, and ends in a high-level application of classification of EEGs for brain-computer interfaces. In between we look at signal processing based on our current understanding of the auditory system and the visual system. Five papers in this issue concern the auditory system, starting at the cochlea, working its way up the auditory nerve, through the brainstem to the auditory cortex. The three vision papers present high fill-factor imagers, binocular perception of motion-in-depth, and color segmentation and pattern matching.

The guest editors would like to thank all the authors for their work in submitting and revising manuscripts. We also thank all the reviewers for their effort in writing reviews and their feedback to the authors.

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Shihab A. Shamma obtained his Ph.D. degree in electrical engineering from Stanford University in 1980. He joined the Department of Electrical Engineering at the University of Maryland in 1984, where his research has dealt with issues in computational neuroscience and the development of microsensor systems for experimental research and neural prostheses. Primary focus has been on uncovering the computational principles underlying the processing and recognition of complex sounds (speech and music) in the auditory system, and the relationship between auditory and visual processing. Other researches include the development of photolithographic microelectrode arrays for recording and stimulation of neural signals, VLSI implementations of auditory processing algorithms, and development of algorithms for the detection, classification, and analysis of neural activity from multiple simultaneous sources.

André van Schaik obtained his M.S. degree in electronics from the University of Twente in 1990. From 1991 to 1993, he worked at CSEM, Neuchâtel, Switzerland, in the Advanced Research group of Professor Eric Vittoz. In this period he designed several analog VLSI chips for perceptive tasks, some of which have been industrialized. A good example of such a chip is the artificial, motion detecting, retina in Logitech's Trackman Marble TM. From 1994 to 1998, he was a Research Assistant and Ph.D. student at the Swiss Federal Institute of Technology in Lausanne (EPFL). Subject of his Ph.D. research was the development of biological inspired analog VLSI for audition (hearing). In 1998 he was a Postdoctorate Research Fellow at the Auditory Neuroscience Laboratory of Dr. Simon Carlile at the University of Sydney. In April 1999, he became a Senior Lecturer in Computer Engineering at the School of Electrical and Information Engineering at the University of Sydney. His research interests include analog VLSI, neuromorphic systems, human sound localization, and virtual reality audio systems.