Modeling Small Oscillating Biological Networks in Analog VLSI

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Abstract: We have used analog VLSI technology to model a class of small os(cid:173) cillating biological neural circuits known as central pattern gener(cid:173) ators (CPG). These circuits generate rhythmic patterns of activity which drive locomotor behaviour in the animal. We have designed, fabricated, and tested a model neuron circuit which relies on many of the same mechanisms as a biological central pattern generator neuron, such as delays and internal feedback. We show that this neuron can be used to build several small circuits based on known biological CPG circuits, and that these circuits produce patterns of output which are very similar to the observed biological patterns.To date, researchers in applied neural networks have tended to focus on mam(cid:173) malian systems as the primary source of potentially useful biological information. However, invertebrate systems may represent a source of ideas in many ways more appropriate, given current levels of engineering sophistication in building neural-like systems, and given the state of biological understanding of mammalian circuits. In(cid:173) vertebrate systems are based on orders of magnitude smaller numbers of neurons than are mammalian systems. The networks we will consider here, for example, are composed of about a dozen neurons, which is well within the demonstrated capabilities of current hardware fabrication techniques. Furthermore, since much more detailed structural information is available about these systems than for most systems in higher animals, insights can be guided by real information rather than by guesswork. Finally, even though they are constructed of small numbers of neurons, these networks have numerous interesting and potentially even useful properties.CENTRAL PATTERN GENERATORSOf all the invertebrate neural networks currently being investigated by neurobi(cid:173) ologists, the class of networks known as central pattern generators (CPGs) may be especially worthy of attention. A CPG is responsible for generating oscillatory neural activity that governs specific patterns of motor output, and can generate its pattern of activity when isolated from its normal neuronal inputs. This prop-Modeling Small Oscillating Biological Networks385erty, which greatly facilitates experiments, has enabled biologists to describe several CPGs in detail at the cellular and synaptic level. These networks have been found in all animals, but have been extensively studied in invertebrates [Selverston, 1985].We chose to model several small CPG networks using analog VLSI technology. Our model differs from most computer simulation models of biological networks [Wilson and Bower, in press] in that we did not attempt to

model the details of the individual ionic currents, nor did we attempt to model each known connection in the networks. Rather, our aim was to determine the basic functionality of a set of CPG networks by modeling them as the minimum set of connections required to reproduce output qualitatively similar to that produced by the real network under certain conditions.MODELING CPG NEURONSThe basic building block for our model is a general purpose CPG neuron circuit. This circuit, shown in Figure 1, is our model for a typical neuron found in central pattern generators, and contains some of the essential elements of real biological neurons. Like real neurons, this model integrates current and uses positive feedback to output a train of pulses, or action potentials, whose frequency depends on the magnitude of the current input. The part of the circuit which generates these pulses is shown in Figure 2a [Mead, 19891.The second element in the CPG neuron circuit is the synapse. In Figure 1, each pair of transistors functions as a synapse. The p-well transistors are. excitatory synapses, whereas the n-well transistors are inhibitory synapses. One of the transistors in the pair sets the strength of the synapse, while the other transistor is the input of the synapse. Each CPG neuron has four different synapses.The third element of our model CPG neuron involves temporal delays. Delays are an essential element in the function of CPGs, and biology has evolved many different mechanisms to introduce delays into neural networks. The membrane capacitance of the cell body, different rates of chemical reactions, and axonal transmission are just a few of the mechanisms which have time constants associated with them. In our model we have included synaptic delay as the principle source of delay in the network. This is modeled as an RC delay, implemented by the follower-integrator circuit shown in Figure 2b [Mead, 19891. The time constant of the delay is a function of the conductance of the amplifier, set by the bias G. A multiple time constant delay line is formed by cascading several of these elements. Our neuron circuit uses a delay line with three time constants. The synapses which are before the delay element are slow synapses, whereas the undelayed synapses are fa.st synapses.We fabricated the circuit shown in Figure 1 using CMOS, VLSI technology. Several of these circuits were put on each chip, with all of the inputs and controls going out to pads, so that these cells could be externally connected to form the network of interest.