HYSTERESIS BASED NEURAL OSCILLATORS FOR VLSI IMPLEMENTATIONS

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Abstract–The actual tendency in most of the work that is being done in VLSI neural network research is to use the simplest possible models to perform the desired tasks. This yields to the use of sigmoidal type neurons that have a static input–output relationship. However, in some cases, especially when the research is close to biological neuron systems emulation, such simplified models are not always valid. In these cases, a neuron model closer to biological neurons is needed, namely the oscillatory neuron [1–4]. For these neurons, when they are active, their output is a sequence of pulses. In this paper we present several circuits that can be set in an active state to yield an oscillatory output.

The difference between the circuits is based on whether the output has two unique output states (off, or on firing at a specific frequency), or has a continuum between the on and off states so that the output frequency changes sigmoidally between zero and its maximum.

I. Introduction

The most efficient computational system is the human brain. It can perform image, sound and sensory data processing beyond the capabilities of the most modern and sophisticated artificial computer systems. This efficiency has motivated many researchers to try to replicate, artificially, the human nervous computing system to solve a variety of complex engineering problems, such as control systems, knowledge processing and signal processing.

A biological neuron is a living cell whose computational processing capabilities are very simple and can be summarized as follows: if the spatial and temporal summation of all its input signals exceed a certain threshold, the neuron will fire a train of electric pulses to all the neurons its output is connected to; if the summation does not exceed the threshold, no train of pulses will be transmitted to the other neurons. This device, the neuron, can be viewed as a voltage controlled oscillator that has an input control terminal such that: beyond a threshold, the oscillator is on, otherwise it is off.

In order to build a device with these properties, an oscillator must be designed that can be turned on and off. A very simple and basic way to implement an oscillator is using a hysteresis device. A hysteresis device is characterized by an equation of the type

$$H(x) = \begin{cases} H^+ & , \text{if} \quad x < x_1 \\ -H^- & , \text{if} \quad x > -x_2 \end{cases} \tag{1}$$

where x is the input to the device and x_1, x_2, H^+ and H^- are characteristic parameters. Fig. 1(a) shows, schematically, equation (1).

Strictly speaking, a hysteresis device has a transfer function as shown in Fig. 1(b). The points for which $H(x) = H^+$ and $H(x) = -H^-$ are stable points, but those for which $-H^- < H(x) < H^+$ are unstable points. Therefore, if $-x_2 < x < x_1$ the output will be either H^+ or $-H^-$ (depending on the initial conditions) but will never be on the nonhorizontal segment.

Connecting a hysteresis device and an integrator in a close loop yields to a triangular/square–wave oscillator. This is depicted in Fig. 2 and the equation that characterizes this system is

$$\begin{aligned} y(t) &= H\Big(x(t)\Big) \\ x(t) &= +\frac{1}{C}\int y(t)dt \end{aligned} \tag{2}$$

which yields the following first order differential equation.

$$C\dot{x} = H(x) \tag{3}$$

The equilibrium point ($\dot{x} = 0$) for this equation is given by

$$H(x) = 0 \tag{4}$$

where $H(x)$ is shown in Fig. 1(b). This point is stable [5] if $d\dot{x}/dx|_{\dot{x}=0} < 0$, which is not satisfied in this case, therefore, the equilibrium point is unstable. Furthermore,

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$$\text{If } H(x) = H^+ \Rightarrow x(t) = x(0) + \frac{H^+}{C}t$$
$$\text{If } H(x) = -H^- \Rightarrow x(t) = x(0) - \frac{H^-}{C}t \quad (5)$$

In this paper, we are presenting four different CMOS structures of hysteresis based oscillators for use in neural systems. All of them are based on the principle just described with the addition of a complementary element able to turn the unstable equilibrium point into a stable one, controlled by some external signal. In the following sections, we will describe the four oscillator structures and give some simulation results.

II. Oscillator Structures

Circuit 1: Consider a transconductance amplifier with differential input voltage V and output current i, such that

$$i = \begin{cases} I_{SS} & \text{,if } V > 0 \\ -I_{SS} & \text{,if } V < 0 \end{cases} \quad (6)$$

and connected in the way shown in Fig. 3 by the circuit comprised of broken lines.

For $V > 0 \Rightarrow i = +I_{SS} \Rightarrow V_d = +E^+ \Rightarrow V = +E^+ - x > 0$, therefore, it must be $x < E^+$ for $i = +I_{SS}$. For $V < 0 \Rightarrow i = -I_{SS} \Rightarrow V_d = -E^- \Rightarrow V = -E^- - x < 0$, therefore, it must be $x > -E^-$ for $i = -I_{SS}$.

This corresponds to the characteristics of a hysteresis device, assuming x is the input and i the output. In order to have an output terminal, we need to replicate the current i. This is done by implementing a transconductance amplifier with double output. The feature of having an output current simplifies the circuit of the integrator in Fig. 2, in the sense that a simple capacitor can be used, as shown in Fig. 3.

In order to be able to turn this oscillator on and off, a nonlinear resistor is connected in parallel to the integrating capacitor. The nonlinear resistor is characterized by the following equations

$$i_R = \begin{cases} I_C & \text{if } x > 0 \\ 0 & \text{if } x < 0 \end{cases} \quad (7)$$

The resulting circuit is shown in Fig. 4(a) and the differential equation that characterizes it is

$$H(x) = C\dot{x} + i_R(x) \quad (8)$$

The equilibrium point ($\dot{x} = 0$) is given by the solution of $H(x) = i_R(x)$, as shown in Fig. 4(b). There are two possible cases. If $I_C < I_{SS}$ (point A) then $d\dot{x}/dx|_{\dot{x}=0} > 0$ and A is unstable (the circuit is oscillating). If $I_C > I_{SS}$ (point B), then $d\dot{x}/dx|_{\dot{x}=0} < 0$ and B is stable (the circuit is not oscillating). The nonlinear resistor can be implemented in CMOS using the circuit of Fig. 5.

If $x > 0$, I_C goes through M_2 and M_4, and is reflected by M_5 back to the input terminal ($i_R = I_C$). If $x < 0$, I_C goes through M_1 and M_3, and $i_R = 0$. The complete CMOS implementation of the oscillator is shown in Fig. 6. Voltage S_k controls I_C and, therefore, the turning on and off of the oscillations.

Circuit 2: The block diagram of Fig. 2 can also be implemented using current mode techniques. A current–mode hysteresis element is shown in Fig. 7 [6]. If $I_x > I_{in}$ then V_o is high, otherwise, V_o is low. Suppose V_o is high because $I_x > I_{in}$. Since V_o is high $I_x = I_A + I_B > I_{in}$. Hence, we can conclude: If $I_{in} < I_A + I_B \Rightarrow V_o$ *high*. Now suppose V_o is low because $I_x < I_{in}$. Since V_o is low $I_x = I_A < I_{in}$. Hence, $I_{in} > I_A \Rightarrow V_o$ *low*. This hysteresis device has a voltage output. If we want to keep using a capacitor as the integrating device in the oscillator, we need to have a current output for the hysteresis element. This can be done in the way shown in Fig. 8. If V_o is high, then $I_{out} = I_C$, if V_o is low, then $I_{out} = I_C - I_B$. Connecting this circuit to a capacitor and converting the voltage across it to a current that is fed back to I_{in}, one obtains the oscillator of Fig. 9. In order to be able to turn this oscillator on and off, we connect, in parallel with the capacitor, a nonlinear resistor characterized by the curve in Fig. 10. The CMOS circuit is shown in Fig. 11.

Circuit 3: If, in circuit 1, we eliminate the nonlinear resistor and make I_{SS} vary between zero and some maximum value, we can turn the oscillations off by making $I_{SS} = 0$. Such a circuit is shown in Fig. 12, where the threshold is fixed by V_T. Furthermore, since I_{SS} controls the frequency of oscillation, we have now a sigmoidal relationship between S_k and the frequency of the output pulses.

Circuit 4: This circuit differs from the previous one in that the output is a sequence of current pulses. The shape of each pulse is fixed, but the time spacings between pulses is variable and depends on the input control signal. The circuit is a modification of circuit 1 in which the output of the hysteresis device is such that H^+ is constant and H^- depends on the control signal and can be made even zero. The expected waveforms are shown in Fig. 13, and the circuit in Fig. 14.

III. Simulation and Experimental Results

Circuit 1 has been fabricated in a standard CMOS $3\mu m$ process and experimental results have already been published elsewhere [7,8]. For completeness of this paper we are showing its measured input/output relationship in Fig. 15.

For Circuit 2, the input/output relationship of the oscillator of Fig. 11 is shown in Fig. 16.

For Circuit 3 (Fig. 12) and Circuit 4 (Fig. 14) the input/output relationships are shown in Figs. 17 and 18, respectively.

CONCLUSIONS

Four different hysteresis based neural oscillator circuits have been discussed. They differ basically, in the input/output relationship of the neuron: either a sharp transition between the on and off states, or a smooth sigmoidal one.

Experimental results have been given for the first circuit. The other three structures, which are modifications of the first one, have been validated through computer circuit simulations. The use of the different structures is application dependent.

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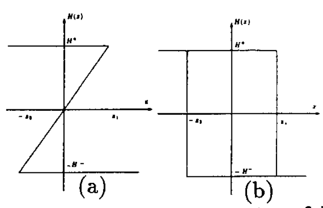

Fig. 1. (a)Transfer Characteristics of Hysteresis Element, (b) Real Input/Output Characteristics of Hysteresis Device

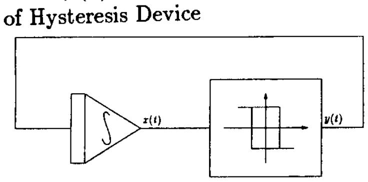

Fig. 2. Triangular/Square-Wave Oscillator with Hysteresis Element

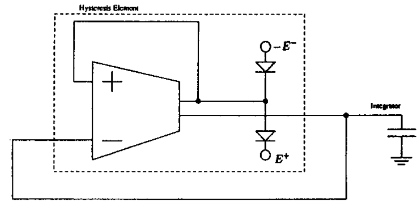

Fig. 3. Hysteresis Oscillator

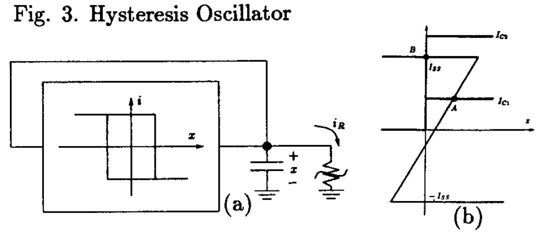

Fig. 4. (a) Hysteresis Oscillator That Can Be Turned On and Off, (b) Equilibrium Point Solutions

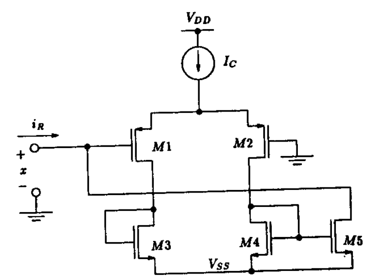

Fig. 5. CMOS Circuit for Nonlinear Resistor

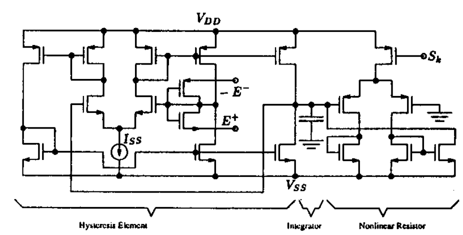

Fig. 6. Complete CMOS Hysteresis Oscillator with On-Off Capability

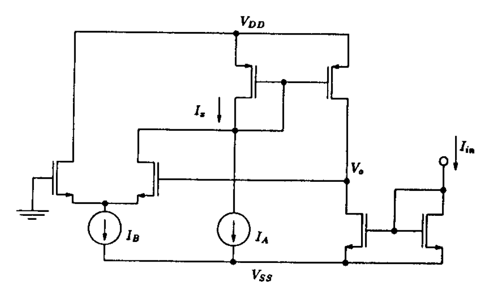

Fig. 7. Current-Mode Hysteresis Device

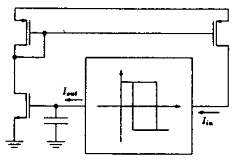

Fig. 9. Current Mode Hysteresis Oscillator

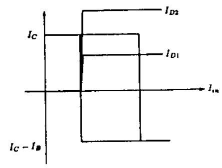

Fig. 10. Characteristics of Nonlinear Resistor and Hysteresis Device

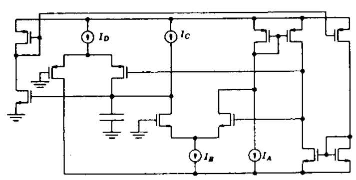

Fig. 11. Complete Current–Mode Hystersis Oscillator with Turn On–Off Capability

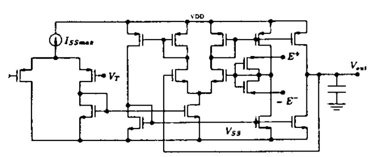

Fig. 12. Hysteresis Oscillator with Sigmoidal Relation Between Input Signal and Output Frequency

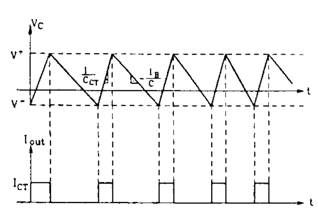

Fig. 13. Expected Waveforms for the Circuit of Fig. 14

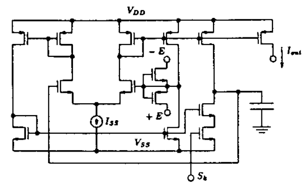

Fig. 14. CMOS Circuit for Oscillator with Fixed Shape Output Current Pulses

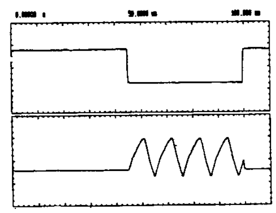

Fig. 15. Input/Output Relationship for Neural Oscillator Circuit 1 of Fig. 10

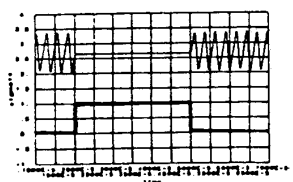

Fig. 16. Input/Output Relationship of the Circuit of Fig. 11

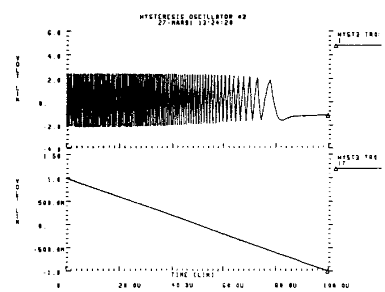

Fig. 17. Input/Output Relationship for Oscillator of Circuit 3 in Fig. 12

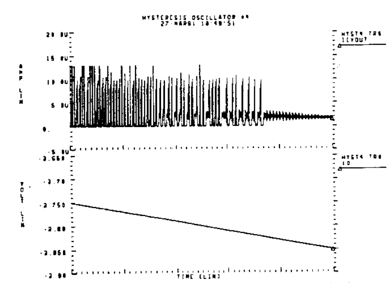

Fig. 18. Input/Output Relationship for oscillator of Circuit 4 in Fig. 14