Overview of Neural-Type Electronics

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Abstract

The main interest of this paper is to present historical and state of the art viewpoints on circuits for neural-type microsystems, these being electronic systems that mimic the important properties of biological neural systems to achieve given behavior. Three general classes of subsystems are discussed and means of construction of large scale systems using them given.

I. Introduction

Neural-type microsystems (NTM) attempt to realize in simple electronic form the desired signal handling characteristics of biological systems. Work in this area is motivated by the desire to use these results in constructing efficient and versatile computer systeds based upon applying engineering principles to the knowledge gained from physiological data of the central nervous system. This philosophy was essentially initiated by H. Crane in the early 1960's and conceptualized in his neursitor [1]. At the time of its conception practical electronic realizations were not available (tunnel diode circuits were, however, used by Nagumo in Japan [2]). This led to a world-wide search for circuits that could be constructed in integrated circuit form with such coming forth in the 1970's from Poland in bipolar form [3] and from the US in MOS structures [4]. Almost simultaneously with this electronic circuit development came a mathematical development of partial differential equations [4] much of which stemmed from the tunnel diode circuits of Nagumo.

In NTM's there are three general classes of subsystems, those handling signal transmission, those combining or mixing signals, and those processing the signals, these being somewhat analogous to the nerve axon, the synaptic junction, and the dynamic cell (soma), respectively. Consequently, this paper surveys primary models for each of the three kinds of signal handling capabilities and such that the main considerations of system performance can be determined by the interconnection scheme of these primary cells. From these, different kinds of large-scale systems can be constructed, such as retinal type, cerebellum type, and hippocampus type.

In section II we discuss the neural-type cells & coupled cells and lines with emphasis upon discretely coupled sections as well as the junctions which allow for convenient interconnections. In section III these are used to build large scale systems. In the final section trends and areas for future development, especially in the areas of neural-type robotics and prosthetics, are surveyed. Because of limited space for background material we refer the interested reader to the textbook of medical physiology by Ganong [5].

II. Neural-Type Cells, Lines and Junctions

In this section we review several of the basic dynamic neural-type cells (NTC)suitable for electronic realizations and their means of interconnection.

The first of these NTC's is the Morishita neuron [6] shown in Fig. 1. In Fig. 1 can be seen the multiple inputs summed through weights and fed to RC dynamics with the output going through a threshold device. All components are readily constructed via integrated circuits; however, a number of components are needed to realize a simple cell. The Morishita neuron has the advantage of simplicity of concept and of the state-space mathematics which describes it.

A more practical NTC for electronic realizations is shown in Fig. 2 [4] where only two MOS transistors are used with a single capacitor for the dynamics and three resistors to establish operating conditions. The left most transistor is just for level shifting while the right one creates the functional nonlinearity needed to get proper characteristics. The simple insertion of a feedback transistor allows for controllable pulse repetition rate with input signal amplitude and, hence, greater flexibility [7].

The use of hysteresis adds considerable versatility to the design of electronic circuits. Consequently, a NTC based upon hysteresis has been developed and is shown in Fig. 3 [8]. In Fig. 3 the hysteresis is obtained through the lower op-amp circuit with operating points being established by the resistors and dynamics supplied by the upper integrator. The input u supplies stimulus to excite the cell or, alternatively, the circuit can be biased to form a neural-type pulse oscillator. Although the circuit uses more components than desired, the idea behind it seems extremely useful and it is thought that with effort devoted to development of hysteresis electronics even more

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* Supported in part by NSF Grant ECS 83-17877 and in part by Grant CCB-84-02 of the US-Spain Joint Committee for Scientific & Technological Cooperation.

practical designs could result.

It should be mentioned that NTC's have slowly evolved in form from the beginnings of the Hodgins-Huxley (H-H) equations [9].
$I=C_m(dV_m/dt)+g_L(V_m-b_1)+g_K(V_m-b_2)+g_{Na}(V_m-b_3)$
where: I=membrane current density $(\mu a/cm^2)$
Vm=membrane voltage (mV) wrt a grounded axis; C_m=membrane capacitance $(\mu f/cm^2)$; g_L= leakage conductance; g_K & g_{Na}=time variable potassium and sodium conductances (given as solutions of complicated nonlinear differential equations). Because of the complexities of the nonlinear behaviors it is very difficult to build a simple electronic simulator of the H-H equations. This has led to various simplifications, probably the most significant of which are the the BVP (Bonhoeffer Van der Pol) model as presented by Fitzhugh [10] who simplified the H-H eqs. to the form
$du/dt=c(w+u-[u^3/3]+z)$, $dw/dt=(a-u-bw)/c$
where a, b, and c are constants satisfying
$1-(2b/3)<a<2$, $0<b<1$, $b<c^2$
z is the stimulus intensity and u is the output. w corresponds to a pair of variables representing a combination of Na inactivation and K activation. Originally these were simulated by Nagumo, et. al. [2], using tunnel diodes but could now be more conveniently realized using op-amp circuits. Finally we mention the Turing-Smale cells. Turing [11] described a mathematical model of the growing embryo in the form of
$dx/dt = ax + by$, $dy/dt = cx + dy$
which he linearized from a more general nonlinear set of equations. Here a, b, c, and d are marginal reaction rates which describe cell characteristics. These are easy to construct but do not contain the critical nonlinearities of the cell; the latter were introduced as Van der Pol nonlinearities by Smale [12] when he coupled these cells together. Because of the practical orientation of these theortical developments, they seem worth pursuing for future circuit developments.

NTC's are of most use when uniformly connected to form pulse transmission systems. Figure 4 shows one of the more practical of the discretely coupled pulse neural-type pulse transmission line (DNTL) circuits [4] in which the cells of Fig. 2 are cascade coupled through interconnecting RC two ports. If bipolar technology is desired, then the cascade sections of Fig. 4 can be replaced by those of Wilamowski, et. al. [3], shown in Fig. 5.

The DNTL's of Figs. 4-5 essentially impelement discretely coupled two ports satisfying BVP types of equations. It is then a simple extension to consider that the sections are uniformly distributed, in which case partial differential equations are used to describe the neural-type lines (NTL) that are simple extensions of the BVP equations given above. To date most of the mathematical analysis of NTL's has considered the distributed case; thus, there is a need for further development of the mathematics for the DNTL's.

Neural-type junctions (NTJ) were mathematically introduced to these symposia by DeClaris [13] with Fig. 6 showing a practical NTJ [14]; its purpose is to combine a number of incoming signals, listed as v_1-v_n, and give an output neural-type pulse. The combining is done by summing currents in the upper resistor and the pulse shaping is done in the output transistor and its RC circuit. Interconnections of NTL's and NTC's are then conveniently accomplished via NTJ's which besides doing pulse shaping can prevent loading and allow for weighting and preprocessing of the incoming signals. It should be noted that the Morishita neuron of Fig. 1 already contains a type of NTJ at its input and, thus, that it is sometimes inconvenient to separate the realizations of subcomponents of NTS's.

III. Large Scale Systems

Basically four classes of large scale NTM's have been considered to date. The first of these mimic the cerebellum and the hippocampus, as studied by Dimopolous [15]. Next are those related to the retinal system, as studied by Ajmera, et. al. [16] (and for which integrated circuits have been constructed [17]). Third are NTM's related to robotics as studied by Niznik [18] where there should be a promising future. Fourth, though probably the first historically, is the area of computer design where the recent studies of Gutierrez [19] pave the way for practical realizations of computers based upon neural-type logic via pulse timing.

Figures 7 and 8 show the structure of the systems studied by Dimopolous where the signal flow graphs are to be implemented by NTC's and NTJ's. At this date computer simulations of the NTM's of these two figures have been made using the Morishita neuron and proven very promising and it remains to implement them in electronic circuit form.

IV. Trends and Areas for Development

Because of the similarity to biological signal processing there is a trend toward studies in related areas. In particular we believe there should be a profitable future for NTM's in the robot and prosthetic fields. Figures 9 and 10 [20] show block diagrams of how implementations may proceed for NTM's in these fields. It seems to us, too, that the logical direction for research on intelligent computers and knowledge based systems is in the NTM area.

We have listed above some of the areas where development is needed, such as for simplified circuits to realize hysteretic systems and hardware implementations of the cerebellum-type systems. Certainly there are many fascinating topics to be delved into and we feel that the surface of this fascinating area has only been scratched.

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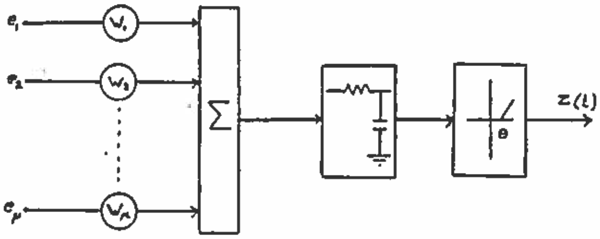

Fig. 1. The Morishita Neuron

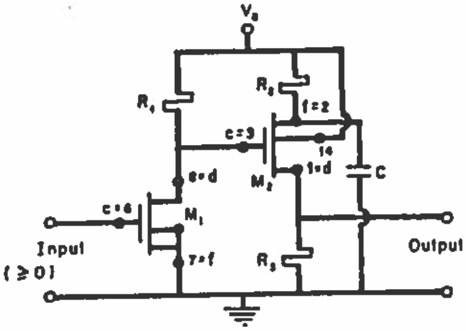

Fig. 2. Simple MOS-RC Cell

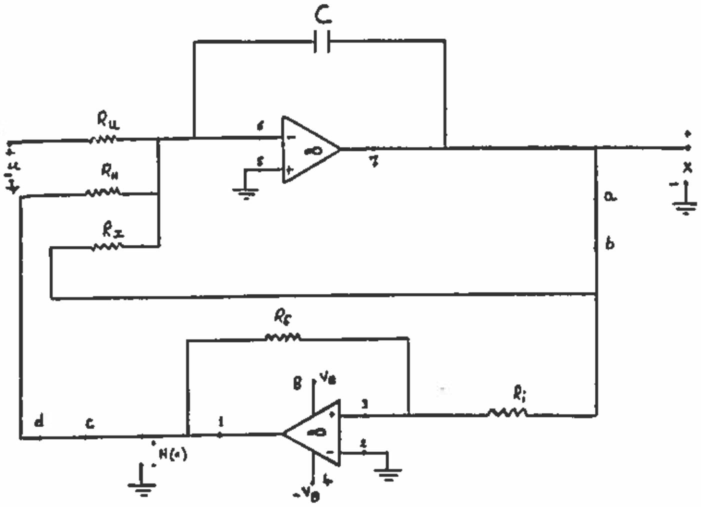

Fig. 3. Op-Amp RC Hysteretic Cell

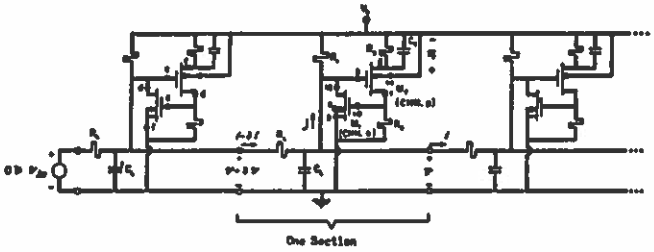

Fig. 4. MOS-RC DNTL

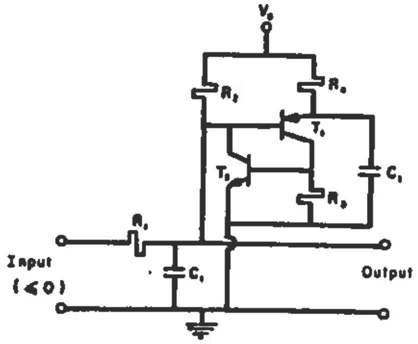

Fig. 5. Bipolar DNTL Section

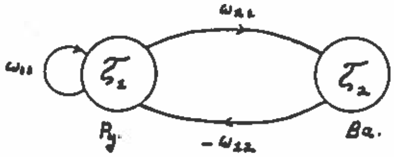

Fig. 8. Hippocampus NTM
[Py=Pyaramidal, Ba=Basket Cells]

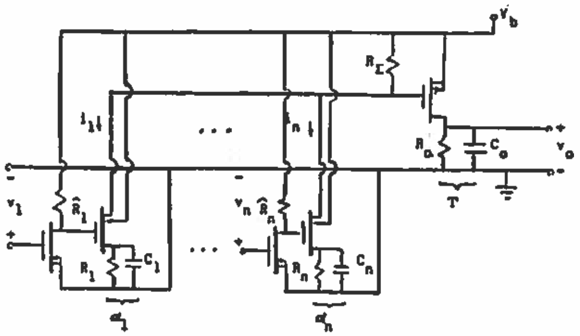

Fig. 6. Excitatory NTJ for Positive Pulses

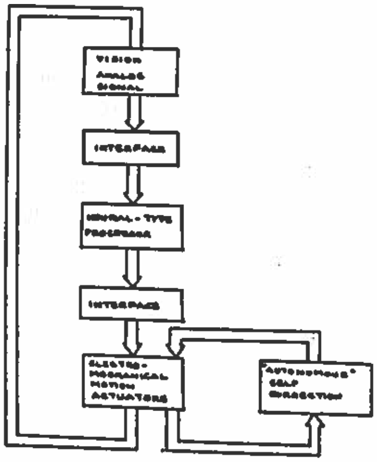

Fig. 9. Neural-Type Robot Processor

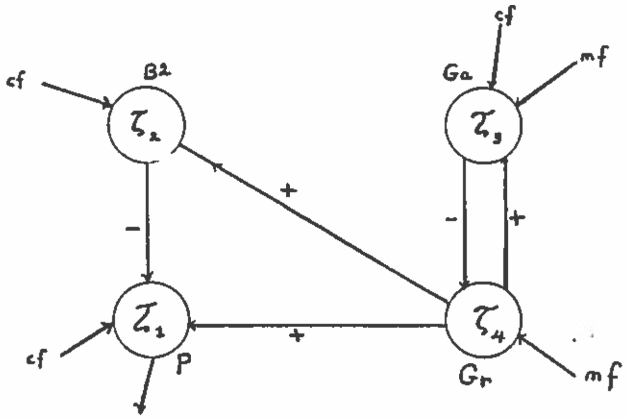

Fig. 7. Cerebellum NTM
[P=Purkinje, Ba=Basket, Go=Golgi
Gr=Granule Cells; mf=moss,
cf=climbing fibers]

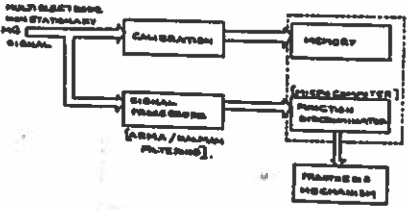

Fig. 10. Neural-Type Prosthetic Processor

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