Integrated Process for Simulating the Retinal Pathway on the Special Purpose Neuronal Assembly Model Array Processor

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Abstract

This paper presents the integration of existing mathematical models of the photoreceptors, the horizontal, the bipolar and the ganglion cells, for simulating the shape recognition processes occurring along the retinal pathway. The simulation of the retinal pathway further involves integration of Biologically realistic models of synapses, Green's function based model of dendritic trees & Hodgkin Huxley(HH) models of neuronal cells. The entire simulation process has been carried out on the special purpose Neuronal Assembly Model Array Processor(NAMAP) model. Integrated simulation of the retinal pathway involving large number of neurons has not been carried out on a special purpose array processor such as NAMAP. Two case studies pertaining to shape recognition process are presented to demonstrate the capability of NAMAP to simulate the retinal pathway.

1 Introduction

Information processing in the brain poses numerous experimental questions and challenging research problems. The brain is endowed with capabilities to recognize objects, human visage, speech and other sensory inputs. The natural visual scene processing is a big challenge even to the most powerful & massive man-made recognition system, whereas the minuscule brain performs such complex tasks in an elegant way. Though this could be due to massive distributed parallel processing[1] by millions of intricately networked neurons, the nature of processing is still obscure. It has been proposed in literature [1] that Vision & Recognition consumes nearly 40% of energy provided by the body. Powerful man -made recognition systems typically consume power equivalent to that generated by a small electric power plant. Such a complex vision system demands a detailed analysis through analytical modelling and simulation.

The modelling of the vision process has been the goal of many a researcher. Several interesting models have been proposed [2][3][4]. However most of these models

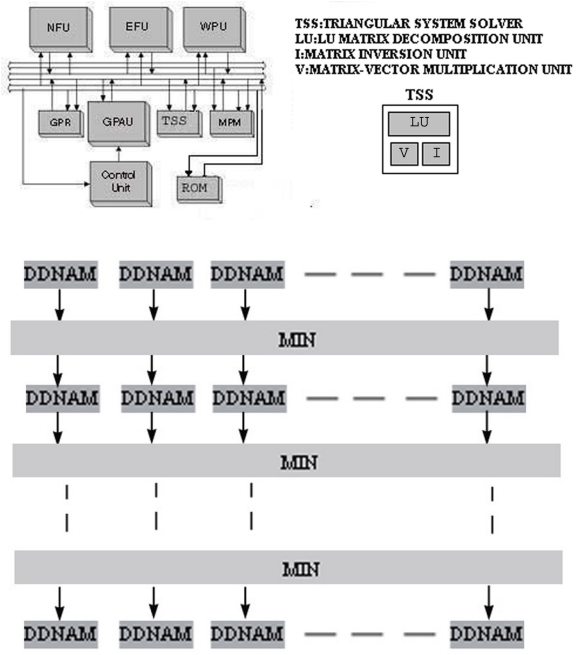

Table 1: The figure on the left (a) shows the DDNAM architecture, the figure on the right (b) shows the NAMAP architecture :MIN-Multistage Interconnection Network

generally incorporate simple integrate and fire neuron model and do not consider the dendritic arborescence. The most realistic mathematical model of the neuron was proposed in 1952 by Hodgkin & Huxley[5]. We abbreviate it as HH for future use. The authors feel that the complexity of HH model has deterred researchers from employing this model in simulations of massive neuronal populations. The enormous computing resources required to model large assemblies of HH neurons has led the researchers to seek simpler models. A general purpose instruction driven NAM (Neuronal Assembly Model) processor for modelling neuronal assemblies was proposed [7]. The architectures of the NAM processor & NAM array processor are shown in Table 1.

This architecture includes a Weiner Process unit(WPU) to help simulate stochastic behavior of neuronal assemblies. Based on a detailed analysis of neuronal assembly

*Names listed at random

[1]Could it be pipelined too?

models including complex dendritic trees, the NAM Architecture was enhanced to DDNAM(Digital Dendritic NAM Processor)[8]. DDNAM has an additional functional unit TSS, the Triangular System Solver to facilitate the simulation of dendritic trees.

General purpose array processors ,cellular neural networks (CNNs) are endowed with massive computing capability but their processing elements are not custom made for modelling neuronal assemblies. This will result in extremely poor performance considering the massive scale of the computations involved in brain modelling. Using DDNAM, a special purpose NAM Array processor(NAMAP)[9] was designed to model massive realistic neuronal assemblies. The papers [7], [8], [9] effectively leveraged nanotechnology towards the design of processor and processor array architectures for the realistic simulation of very large neuronal assemblies. The architecture of NAMAP is shown in Table 1.

Depending on the clock frequency($\geq$ 1 Ghz) and the simulation time step,neuronal assemblies containing a few *hundreds* of neurons can be simulated in a DDNAM processor [9]. NAMAP consists of a number of DDNAM processors. The number of DDNAMs in the NAMAP model can be varied to simulate very large number of neurons. There is no existing hardware design models to match the capabilities of NAMAP and its simplified programming environment.

New language constructs were proposed matching with the architecture of the DDNAM processor and the NAMAP, to evolve NAM Language, the NAML. Usage of these constructs simplifies the simulation task of the researchers. NAML includes special constructs to create,connect and simulate different models of neurons. These constructs are shown in the table 2. Further in this paper, few more constructs are provided for simulating the visual pathway. These are discussed in section 3.

This paper presents an integrated process for simulating the photoreceptors, the horizontal, the bipolar and the ganglion cells. This integration process is employed towards simulation of the shape recognition processes of the retinal pathway. This further involves integration of realistic models of synapses, Green's function based model of dendritic trees & HH models of neuronal cells. The entire simulation process has been carried out on the NAMAP model.

DDNAM's capabiility to solve the complex differential equations of the HH model is presented in section 2 of this paper. Section 3 focuses on mapping the retinal pathway onto NAMAP. Advanced NAML constructs for retinal pathway modelling are presented here. Section 4 discusses the simulation results in detail.

Table 2: Basic Constructs of the NAML Language.

Constructs	**Parameters**
Createleaky	R, C, λ
Createpassive	$R, C, N, L_1 \ldots L_n, \lambda$ L_i is the length of dendrites
Createhodghux	$m, n, h, g_{Na}, g_k, E_{Na}$, $k, E_k, g_L, E_{REST}, \lambda$.
Connectleaky	$Dest, Source1 \ldots n$
Connectpassive	$Dest, Source1 \ldots n$, $x_1, x_2 ... x_n, x_i$ is the point of connection.
Connecthodghux	$Dest, Source1 \ldots n$
Simulate	$leaky \vert passive \vert hodghux$

R-Resistance, C-Capacitance, λ-level, $g_{Na}, g_k \ldots$ are conductances, $E_{Na} \ldots$ are rest potentials

Table 3: Hodgkin Huxley equations for Ganglion Cells

Na^+ channel	$\alpha_m = \frac{-0.6(E+30)}{e^{-0.1(E+30)}-1}$	$\beta_m = 20e^{\frac{-(E+55)}{18}}$
	$\alpha_h = 0.4e^{\frac{-(E+50)}{20}}$	$\beta_h = \frac{6}{e^{-0.1(E+20)+1}}$
Ca^+ channel	$\alpha_c = \frac{-0.3(E+13)}{e^{-0.1(E+13)}-1}$	$\beta_c = 10e^{\frac{-(E+38)}{18}}$
K^+ channel	$\alpha_n = \frac{-0.02(E+40)}{e^{-0.1(E+40)}-1}$	$\beta_n = 0.4e^{\frac{-(E+50)}{80}}$
A channel	$\alpha_A = \frac{-0.006(E+90)}{e^{-0.1(E+90)}-1}$	$\beta_A = 0.1e^{\frac{-(E+30)}{10}}$

2 Solving HH Model on DDNAM Processor

The action potential in HH model is due to inflow of the cations from the extracellular fluid into the neuron. Initially, Sodium ions flow from outside of the cell to inside and later potassium ions flow out (refractoriness). This mechanism leads to the generation of action potential. The HH model is as follows.

$$I(t) = c\frac{dv}{dt} + g_{Na}m^3h(u - E_{Na}) + g_K n^4(u - E_K) + g_L(u - E_L) \quad (1)$$

The three variables m,n and h are called gating variables. These evolve according to the following differential equations

$$\begin{aligned} \dot{m} &= \alpha_m(u)(1-m) - \beta(u)m \\ \dot{n} &= \alpha_n(u)(1-n) - \beta(u)n \\ \dot{h} &= \alpha_h(u)(1-h) - \beta(u)h \end{aligned}$$

The architecture of the functional units of the DDNAM processor helps simulate the HH model given by the differential equations. The Hodgkin Huxley Equations, for the Ganglion Cells are given in Table3. The solution of the differential equations for Ganglion and Cortical

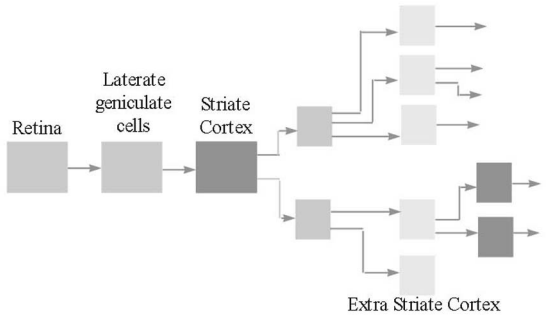

Figure 1: Visual Pathway

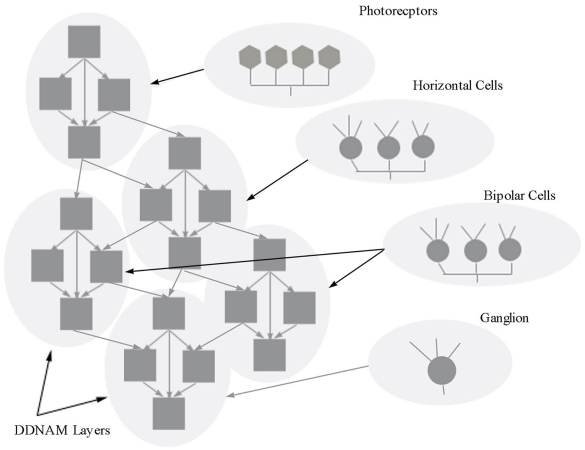

Figure 2: Mapping the Retinal Pathway onto NAMAP

cells have been studied. In fact there is an additional Ca^{2+} current in Ganglion cells[1] . Employing the HH model, the dendritic arborescence, the soma, and the synapse have been integrated in the simulation process. This integrated simulation process has been mapped on NAMAP model. Sections 3 & 4 present the same.

3 Mapping the Retinal Pathway on the NAM Array Processor

The various layers of the retinal pathway are mapped onto different layers of NAMAP. The dendritic interconnections across layers are effectively substituted by the multistage interconnection networks(MINs) between two layers of the NAMAP. The visual pathway is shown in the Figure1. The mapping of the retinal pathway onto NAMAP is pictorially explained in Figure 2. Each layer of the retinal pathway is mapped onto a network of DDNAMs .

Table 4: Advanced Constructs of the NAML Language.

Constructs	Parameters
Rcell	ξ, N
Gang	ξ, M
ConSynapse	$R1, R2, \ldots, G1, G2, \ldots$
Corti	S
Lgen	S
Recognise	

ξ-Type of the Neuron model, N-No. of vertices of the photoreceptor, M-No. of neurons in the Ganglion level, R-Instance of Rcell, G-Instance of Gang, S-Size of the region in terms of levels

3.1 Visual Pathway

The visual pathway proceeds from photoreceptors, bipolar cells ,amacrine cells, ganglion cells, Laterate Geniculate Nucleus(LGN) and finally the striate cortex. The axons of the ganglion cells of the retina form the optic nerve, which projects in an orderly fashion to the lateral geniculate nucleus in the thalamus [15]. The LGN projects to the ipsilateral primary visual cortex, or V1, in the striate cortex [16]. The cortex has a complete map of the retina. The extrastriate areas form the higher order visual areas in the brain. Each of the layers in the visual pathway is involved in a specific information processing activity. Figure 1 shows the parallel pathways of the visual system. Each structure(shown as box) consists of millions of cells, aggregated into sheets. Each receives inputs from one or more structures at lower levels in the path and each sends its output to several structures at higher levels. These paths proceeds to several layers beyond the primary cortex [6].

3.2 NAML Constructs

The NAML language proposed in [9] is capable of modelling any neuronal population in terms of user friendly instructions. Here, we add to NAML a set of constructs that are specific to the visual pathway. The constructs and their parameters are tabulated in Table4.

The retina possesses a large number of photoreceptor cells. These photoreceptors are modelled using the Rcell construct. The connections between two neurons is established through a synaptic junction. In NAML, Consynapse establishes the synaptic connection. Gang construct defines the ganglion cells. Recognise construct initiates the recognition process. A few more constructs have been included for future application. This includes the Corti construct that models the complex cortical region in the brain. Lgen models the LGN region.

Table 5: A Sample NAML Program

```
main module;
 Rcell R1 (leaky,5);
 Rcell R2 (hodghux,6);
 Rcell R3 (hodghux,4);
 Rcell R4 (passive,5);
 Gang  G1 (hodghux,4);
 Gang  G2 (hodghux,5);
 Consynapse (R4,R3,G1);
 Consynapse (R1,R2,G2);
 Recognise();
 endmain;
```

A sample NAML program for defining the structure of a part of the visual pathway is given in Table 5. The power of NAML is evident when NAML programs are compiled using NMC(Neuron Model Compiler)[9].This is because the object code that NMC generates is specific to the special purpose functional units of the DDNAM processor.

3.3 Mapping Algorithm

The mapping of the retinal pathway onto the NAMAP involves the mapping of several neuronal assemblies. This is shown in the figure 2. The mapping algorithm is given in Table 6.

4 Simulation

Table 6: Algorithm for Mapping Neuronal Assemblies on to NAMAP

```
Input: NAML code specifying the neuronal assembly
Output:Allocation of neurons to NAMs
  start
    1.Analyse the input and extract the
      communication graph using tree extraction
      algorithm.[16]
    2.'ano'=No. of neurons in the assembly
    3.Based on 'ano' specify no. of layers in
      array processor 'lno'
    4.Specify 'nnam'=no of NAMs per layer
    5.Set the no of neurons to be simulated in
      a single  NAM = 'X'
    6.Partition the communication graph into
      Z subgraphs using "equal node" graph
      partitioning technique.[15]
    7.Check for completeness and adjacency of
      sub graphs
    8.Allocate to NAMs their corresponding
      sub graph of neuron(s). Pass control for
      data and instruction transfer to the NAMs.
      Host computer then sends control to the
      switches in MIN.
 End.
```

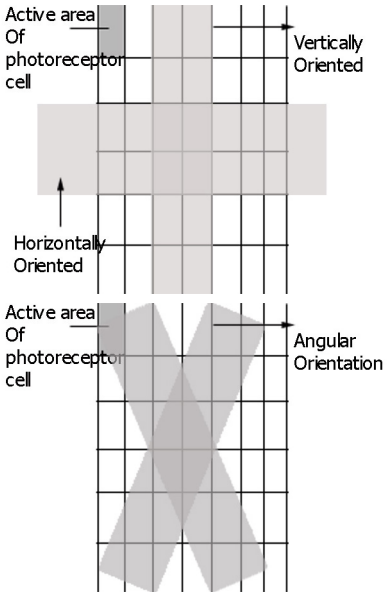

Table 7: The Oriented stimuli presented as input

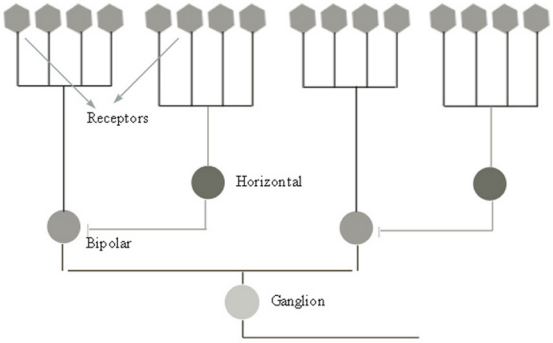

Figure 3: Structure of the Retinal pathway

An exhaustive event driven simulation of the retinal pathway was performed integrating different characteristics of the neuron. The Recognise() construct initiates this complex simulation process. The algorithm for N neurons, S synapses and simulation time step (dt) is shown in Table 9.

The simulation encompassed the dendrites, the soma and the synapses. The soma was simulated using HH models of the respective neurons. Models for ganglion cells were incorporated based on [14] and [6] . Synaptic models given in [10] & [13] were employed in the simulation process. The NAMAP model efficiently simulates the complex retinal pathway. The basic structure of the pathway simulated is shown in Figure 3.

The simulation involved around 500 neurons spread

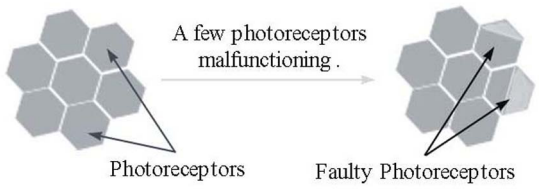

Figure 4: Simple Fault Model for the Photoreceptors

among the different layers of the pathway, upto ganglion cells. The authors believe, such large collection of neurons have not been simulated on a single array processor model before. This emphasizes the power of our NAMAP.

The shapes considered are a rod and a circular disc. Table 8 shows the rod and circular disc in different orientations(stimuli shown in Table7) relative to the receptor cells and the corresponding output spikes from the ganglion cells have also been shown. The final spike output from the last stage,ganglion region, containing four neurons is shown in the Table8. The spike output from twenty five ganglion neurons are also shown. The receptive field of some neurons respond best to a vertical bar of light that covers the excitatory area. The response is less when the bar is tilted or placed horizontally since it covers the inhibitory area.

When the input stimuli is displaced by a few pixels, the output spikes also get displaced.This is evident from the spikes generated from the ganglion region. When a circular disc is placed in front of the photoreceptor cells, the area covered by the disc is more and hence more is the spiking activity. The variation in rate of spikes is noticed when the disc is placed at an angle. This is due to variations in the relative distances across the photoreceptors and the portions of the disc.

5 Application

The objective of having proposed the NAMAP model in [7] [8] [9] is to evolve a powerful tool for fault modelling the complex regions of the brain. These fault simulations will tremendously help in the diagnostic processes of complex complications that may take place in the brain functioning. This may lead to new discoveries also. Malfunctioning of different regions of the visual pathway can take place due to physical damages to neurons. The abnormal electrical activities also impair neurons. A part of the retina may get damaged and the usual hexagonal cells may become polygons.A simple case is shown in figure 4.

Table 8: Spiking activity for different orientations Row 1:vertical rod,angular rod; Row 2:Horizontal Rod, Impulse encoding from 25 Ganglion cells Row 3:flat circular disc,angular circular disc; Row 4:Time Shifted vertical rod stimuli

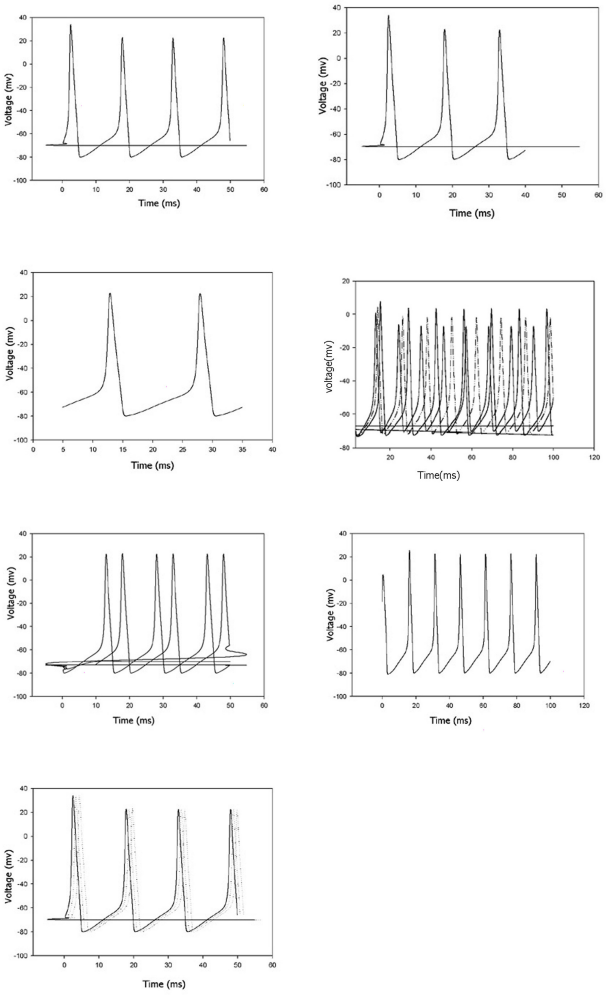

Table 9: Event driven algorithm for *Recognise()* construct

```
CT = StartTime
while CT <  TimeOut do
  for all Neurons[i] do
    for all ActiveInputSynapses[j] do
       Perform dendritic operation
    End for
  Propagate input
  Perform relevant operation as per neuron model
  Trace the spike decay
  Record firing time(i)
  Update event list for all postsynaptic neurons
  End For
CT += TimeStep
end while
```

6 Conclusion

This paper presents simulation of the Retinal pathway on the NAMAP, integrating biologically realistic models of synapses, Green's function based model of dendritic trees & HH models of neuronal cells. New NAML constructs suitable for Visual Pathway are proposed. To demonstrate the capability of the retinal pathway simulation on the NAMAP, two case studies pertaining to shape recognition process are presented. These case studies include analysis of the spiking outputs from the ganglion stage corresponding to a rod and a circular disc under different orientations. Simulation results are provided to substantiate the case studies.

The proposed simulation process of retinal pathway on the NAMAP model can greatly help simulate complex faults along the retinal pathway and eventually along the visual pathway. This fault modelling can be employed for evolving a detailed diagnostic process for abnormalities that might affect the retinal and visual pathway. Further, the simulation process presented here can be applied by neuroscientists and researchers towards possible new discoveries.

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