Bio-Inspired Integrated Circuits For Signal Perception and Processing

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ABSTRACT

Bio-inspired systems utilizing neural networks (NNs) and genetic algorithms (GAs) are presented for communications, networking information dissemination, and real-time control in signal perception and processing (SPP). VLSI and nano circuits and systems will provide affordable, reproducible, and reliable front-end high performance SPP. Sample applications are presented for integrated intelligent ***E-Nose Systems***, and ***Communication Systems*** which include: **i-**Self-Organizing feature Map for discovery, **ii-** Recurrent Dynamic Neural Networks (NNs), with output neurons feedback and feed forward arrays for noisy signals, **iii-** Reinforcement NNs for applications with only key features, rather than a known model, **iv-** Spiking NNs that adjust their synapses subject to changes in the environment, and **v-** Genetic Algorithms for characterization and optimization.

1. INTRODUCTION

Efficient communication applications require: (1) Compact, low cost, and versatile sensing devices. (2) Intelligent signal processing and perception, and (3) Smart and flexible information transmission. Fast, cognitive, and compact integrated systems for accurate perception and signal processing are necessary for communications, information dissemination, sensors and actuators interface and real-time control. Bio-inspired systems provide the advantage of compact size and faster data storage and direct interface to physical and biological systems with fast processing via architectures similar to parallel processing computers. To mimic the biological abilities of acquiring knowledge and training along side that of genetic mutations and crossover an integrated system of neural networks (NNs) and genetic algorithms (GAs) hold promise for real-time solutions in classifying, identifying and quantifying chemical and bio-chemical agents. Significant design differences exist between the type of perception intelligence required in implementing a biotechnology system, and that for other ordinary applications.

To process/store/analyze signals acquired from multiple physical sensors, or to form networks with multi-users hybrid systems, with flexible and adaptable artificial intelligence implementations are needed.

Bio-inspired nano-systems have architectures similar to parallel-processing computers. Also, in practical sensors and actuators systems, the biological outputs can be easily coupled to electronic neural networks for SPP. Signal processing have usually been approached by traditional computer algorithms and digital methods. Although these methods have been relatively successful, they are usually computationally intensive and can be very complex. Another drawback of these methods is that they lose their usefulness, when the problems concerned are uncertain or stochastic in nature, e.g. as in many important filtering and prediction problems and for processing signals from multi-measurement sensors, or multi-users networks.

This paper classifies the overall system objectives to develop a bio-inspired/intelligent signal perception and processing system. Presented are also sample embedded, tested, and evaluated VLSICs of intelligent SPP systems for communications and Electronic-Nose.

2. BIO-INSPIRED INTELLIGENT SIGNAL PERCEPTION AND PROCESSING

Bio-inspired SPP systems also facilitate for interfacing of bio-systems to circuits for high performance and reliability. Bio-Inspired sub-micro-systems with intelligent SPP shall facilitate for further advanced applications such as adaptive computing systems, target recognition, bio-chemical sensing and detection, smart accelerometers and nano technology autonomous applications. Intelligent bio-inspired SPP systems include: (I) SOFM neural networks are presented for pattern discovery (II) RDNN approach and implemented sub-micron system is presented for application specific adaptation of the network to optimize the quality of service (detect clear signals from noisy ones.) (III) Reinforcement neural networks (RNN) are presented for solving problems with networks congestion,

combined priorities and limitations, as well as networks connection admissions control. A sample of implemented RNN nano-systems, at the MSDL, is presented with emphasis on mixed analog/digital signal processing. **(IV)** A genetic algorithm (GA integrated system is presented, and proposed for signal optimization, network congestion, connection admission control, and efficient resource management based on priority (fitness) selection.

All of the above mentioned alternatives of bio-inspired systems may be applied for any signal perception and processing, in particular when interfacing with natural biological systems. Practical applications for depicting the mammalian olfaction system, the Electronic-Nose (E-Nose) are addressed, with hardware IC implementations for three and four volatile organic compounds. A novel spiking NN approach shows promise for a closer depiction to the mammalian olfaction system. **(V)** Spiking Neural Networks (SNN), based on linear integrate and fire approach provides for excellent E-Nose implementation. Learning within SNNs use plastic neurons with environment based synaptic threshold.

3. INTELLIGENT SPP APPLICATIONS

3.1 Communication Networks

Bio-inspired SPP are considered here for dynamic communications network problems including: (1) Connection admission control; (2) Network bandwidth control; (3 Efficient resource management; (4) Combined priorities and constrains of service control; and (5) Application specific adaptation of the network to optimize quality service for run time signal processing. A sample system design scheme for multi-user communication networks is shown in Fig.1.

3.2 RDNN for Noise Cancellation

Recurrent Dynamic NNs (RDNN) present a pattern recognition method for classification of several given noisy signal, time or space dependent, waveforms (y(t)). The waveforms are decomposed into orthogonal basis, and the coefficients of decomposition are computed by a RDNN and taken to be feature vectors for discrimination among waveforms. *Q(t) is the weighting matrix*, to improve the scaling of the problem, and to reflect the relative importance of different errors. *y(t) is a given (possible noisy) waveform,* and GT(t) x(t) = g1(t) x1 + g2(t) x2 + … + gn(t) xn is its projection on the assumed elementary basis. The optimum decomposition coefficients minimizing F, the error integral are produced at the output of the recurrent dynamic neural network after convergence. The output is then a nonlinear sigmoidal operation on the resulting state [z i],

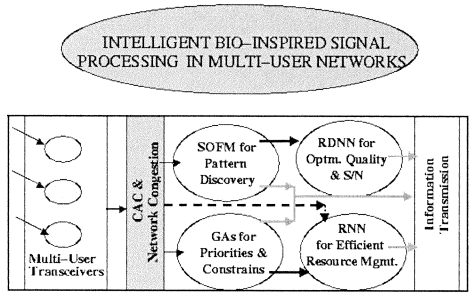

Figure.1 Bio-Inspired system module for multi-user communication networks signal perception and processing

where g(z i) = k i /(1+e(-li z i)), to modulate the output response of each computational element, while the gain constants (ki) allow for control of speed of convergence [12-13].

$$T_{ij} = -2\int_0^{\eta} g_i^{\mathrm{T}}(t)Q(t)g_i(t)dt$$

RDNNs need to know the model of signals, thus they are usually not suitable for direct interface to sensors outputs. Severe interaction between coefficient values limit the hardware implementation, Fig.2.

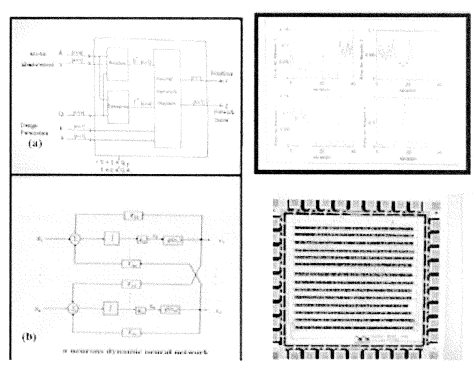

Figure.2 RDNN system, block diagram with 'y' as incoming signal, N-neurons. Outputs of 4-neurons system. IC layout of a 2-neuron RDNN chip.

3.3 Electronic Nose

In the case of chemical detection, fast pattern and signal recognition is very important to system performance for bio-signal and biochemical analysis.

Analog's smaller silicon real-estate consumption will permit much finer-grain processors than digital. This will force applications designers to use analog front ends for future bio-systems that must process information in near real-time. A general block representation of system designs for bio-chemical detection, is shown in Fig.3, incorporating biologically inspired artificial intelligence (neural nets and genetic algorithms.)

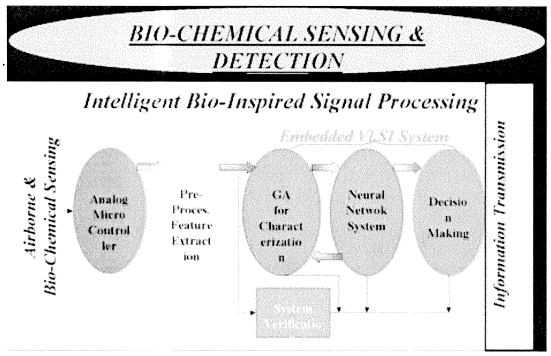

Figure 3 Block representations for Bio-Chemical sensing and detection, using Bio-Inspired signal perception and processing

$$S_i = 2\int_0^{\eta} g_i^{\mathrm{T}}(t)Q(t)y(t)dt.$$

Figure. 3 depict an overall system for bio-chemical sensing and detection with bio-inspired SPP. The presented system uses: 1) an integrated analog multiplexer; 2) A novel genetic algorithm system for measurements characterization; 3) an implemented Reinforcement NN system; and 4) smart information transmission unit. The four units of the system have been designed, fabricated and tested. Mixed-signal implementations provide appropriate interface with chemical/bio-chemical sensors, sensor-arrays, and the added programmability. Sample hardware VLSIC design, implementation, testing and evaluation of E-Nose are presented in the following three sub-sections.

3.3-i GA and RNN E-Nose System

A novel pre-processing Genetic Algorithm (GA) stage for measurement characterization is designed. The GA system uses Half-Sibling and A Clone (HSAC) [2] approach which accepts dynamic inputs and utilized both crossover and mutation to reach convolution in no more than 10 iterations (generations). The HSAC GA system is also simple for hardware implementation, Fig. 4. The HSAC system is used to determine characteristic weights for hardware implementation of the following RNN system.

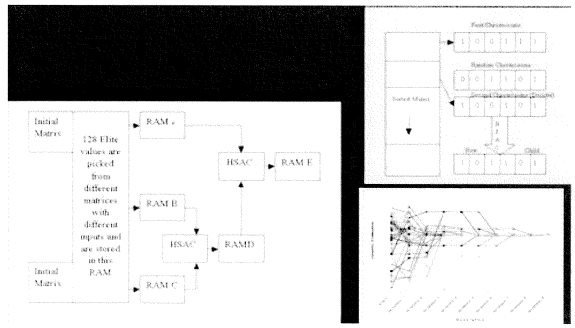

Figure 4. GA approach, half-sibling-and-a-clone (HSAC) for dynamic bio-chemical sensors characterization [2]

A Reinforcement Neural Network (RNN) system is developed for classification, identification, and quantification. RNN approach is optimum for usage with systems of known key features only, as chemical sensors measurements.

The design, implementation and test results of an analog MOS, Reinforcement NN (RNN) by compact and novel sub-circuits is shown. System implementation has been optimized for compactness and tolerance to sensor measurements (minimum silicon area and maximum input signal swing with intelligence to handle measurements uncertainty due to operational, environmental, and aging factors. The RNN embedded chip, consisting of two three-feature neurons occupied 0.114 mm2 using 1.5um CMOS technology, Fig.5. Thus the enhanced system will facilitate for real-time, high detection resolution of bio-chemical agents.

3.3-ii SOFM

A modification of Kohonen's SOFM and its dedicated parallel hardware implementation have been designed, developed and fabricated. This neural net has two layers, and employs unsupervised learning to discover novel ordered relationships among input data patterns. The similarities among patterns are mapped into corresponding distance closeness, which are transmitted to a competitive output layer. For a 5x5 competitive layer, system partitioning (a), and a tiny chip implementation of a processing unit (PU) with associated computations (distance, weight update, weight compare, and neighbor comparison operation) are shown in Fig. 6. with tiny chip implemented using MOSIS 2 um technology, operating at 10 MHz.

3.3-iii SPIKING NN System

Spiking NNs are noise tolerant, offer environmental based synaptic threshold, and are massively parallel, which mimics the mammalian olfactory system. More details about our novel SNN olfaction system are given in [9].

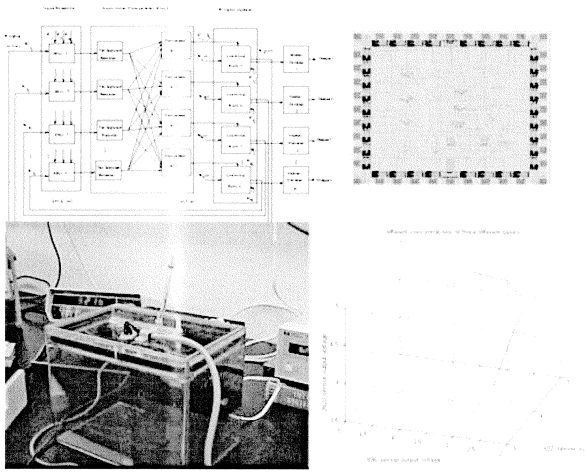

Figure 5. a) RNN with 4-neurons and 3-features. b) Analog VLSIC of 2-RNN neurons (16 may fit on a tiny chip with 1.5um CMOS technology [5], c) Experimental setup and outputs.

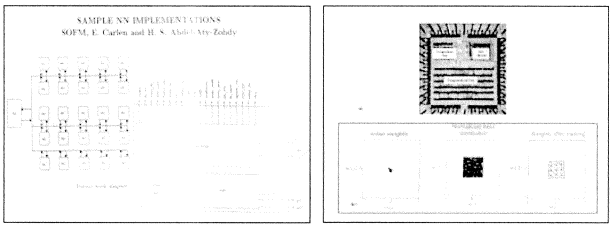

Figure 6. SOFM system (5x5) neurons. Tiny chip for pattern discovery. Feature map after 4000 iterations.

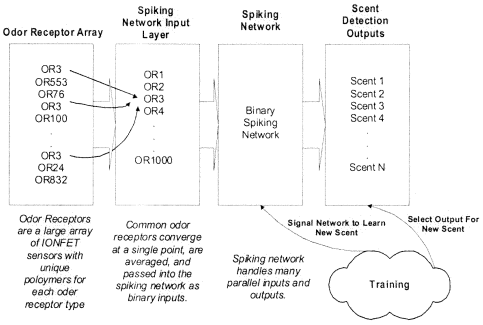

Figure 7. E-Nose system with Spiking NNs.

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4. SUMMARY AND CONCLUSIONS

Bio-inspired integrated nanosystems including Neural Networks (NNs) and Genetic Algorithms (GAs) will provide affordable, reproducible, and reliable front-end instrumentation, components and sub-systems. Efficient bio-inspired applications require: (1) Compact, low cost, more diverse and versatile sensing materials and devices. (2) Intelligent signal processing and perception. (3) Smart and flexible information transmission. . Bio-applications that employ fast pattern and signal recognition will prove very important for future chemical detection systems in gas vapor classification, spectrum signature, bio-signal and biochemical analysis.

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