Input coding for neuro-electronic hybrid systems

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LIQUID State Machines have been proposed as a framework to explore the computational properties of neuro-electronic hybrid systems[1]. Here the neuronal culture implements a recurrent network and is followed by an array of linear discriminants implemented using perceptrons in electronics/software. Thus in this framework, it is desired that the outputs of the neuronal network, corresponding to different inputs, be linearly separable. Previous studies have demonstrated this by either using only a small set of input stimulus patterns to the culture[2], large number of input electrodes[3] or by using complex schemes to post-process the outputs of the neuronal culture prior to linear discriminance[4]. In this study we explore ways to temporally encode inputs into stimulus patterns using a small set of electrodes such that the neuronal culture's output can be directly decoded by simple linear discriminants based on perceptrons. Based on this, we demonstrate that the neuronal culture can be used as a kernel to transform inputs which are not linearly separable in a low dimensional space, into outputs in a high dimension where they are linearly separable. Thus simple linear discriminants can now be directly connected to outputs of the neuronal culture and allows for implementation of any function for such a hybrid system.

I. NEURONAL CULTURES AND ELECTROPHYSIOLOGICAL RECORDINGS Neuronal cultures were grown from hippocampus of 1-2 day old rat pups on MEA's with 120 electrodes. Recording and stimulation were carried out using MEA-2100 system (*MultiChannel Systems, Germany)* on 25-50 DIV *in vitro* neuronal cultures.

II. INPUT CODING, OUTPUT DECODING AND EXPERIMENTS The system can have *n* inputs. Each input was assigned to an electrode. A stimulus pulse was applied to the electrode with a delay proportional to the value of the input. Output vector was defined as a binary 120 element vector with a 1 for electrodes which showed a spike in a time window post stimulus. Output decoding was done using a perceptron which was trained to identify a plane which separates the output pattern corresponding to an input from the rest. In all experiments,each pattern was repeated 45 times in a random order with a time delay of 250ms.

Experiment 1*:* 56 patterns were created from 8 electrodes by taken 2 at a time. Time delay between firing of two electrodes in a pattern was varied from 0.5 to 50ms..This investigated the interaction of different inputs and the required timing.

Experiment 2*:* 40 patterns were made from 8 electrodes taken 8 at a time to check if longer sequences give similar results.

Experiment 3*:* 15 linearly non separable inputs from a 3D space(fig a) were encoded for the neuronal culture using 3 electrodes using the input coding scheme. This was to demonstrate the use of the culture as a kernel for a transformation.

III RESULTS The experiments were done on 5 cultures and all show similar results as described below.

A. *Pairing of stimulated electrodes and their sequence generates linearly separable outputs from the culture. They had to be within 2ms for such interaction. Results and comparison with similar works are shown in the Table 1 below.*

B. *Linearly non separable points in low dimensional space at input are separable at output. 13/15 inputs are classifiable in his way with >85% accuracy (45 samples for each pattern) .*

Ref	Electrodes for Input/Output	Parameters for output	Number of patterns	Output Decoding
[2]	2/128	128	2	Spatial
[3]	59/59	~944	10HFS, 60LFS	Spatio-Temporal
[4]	~59/59	944	16	Spatio-Temporal
Current	8/120	120	45 in E1, 30 in E2	Spatial

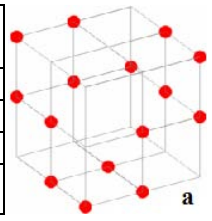

Table 1 : Comparison with similar studies. **Figure a** : Points in 3D Space for Experiment 3

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