METHODS FOR THE ASSESSMENT OF MULTINEURONAL RELATED AND MULTIVARIATE ACTIVITY PATTERNS AND SOME CNN ARCHITECTURE IMPLEMENTATIONS

Theses of the *Ph.D.* Dissertation

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Introduction

This doctoral work is dealing with three different multivariate pattern analysis problems, and what encapsulates them into one work is the 'analog' and 'logic' (analogic) approach in their background and their direct or indirect relation to neurobiology.

Cellular Nonlinear/Neural Network Universal Machine (CNN-UM)[9] is the platform for practical implementations of the analogic ideas: CNN provides a well-defined mathematical and a hardware feasible physical framework to study the emergence of patterns encoded by the local interactions of identical cells. The easy VLSI implementation of the cell array is the most important advantage compared to other modeling frameworks.

In the first thesis through the example of multiple neural activity data I try to show that problems with spatially independent – or independently processed – signals can also be translated effectively to the language of CNN[3][4]. One of the fundamental questions in neuroscience concerns the nature of the neural code: how the information or signal that one neuron communicates to others is embodied in its biophysical processes.

I describe statistical models for spike trains which bear on rate versus temporal coding distinctions, and develop hypothesis tests for the purpose of relating the models to experimental data. My goal was to develop definitions and methodology to assess the existence and nature of fine temporal structure in the neural records using assumptions which are compatible with the theoretical goals of neuroscience[10],[11]. Implementing these methods, beside the design of traditional computational algorithm, I also considered the reformulation of the problem of spatially independent signals enabling the much faster parallel computation.

In the second thesis I prove that effective CNN-UM implementation of a special 'fine-grained' type genetic algorithm is feasible[7]. A genetic algorithm (GA) is a search technique to find approximate solutions to combinatorial optimization problems: classical domains are characterized by fitness (optimization) functions with

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complex fitness landscape (many local minima) on high dimensional data sets. Typical examples include timetabling, scheduling problems, automated design, but here I show the suitability of binary GA in connection with the analysis of multi-dimensional (multi-channel) neural activity data.

The last thesis group is dealing with collision prediction: analysis of situations when the motion of an object could end up with a useful (e.g. for a predator) or disadvantageous (e.g. for a prey) collision with the observer/sensor.

The locust LGMD neuron is evolutionary honed to detect potential collisions with predators and provide a collision avoidance reaction. I show analogic collision avoidance systems partly derived from the computer model of the locust visual system and demonstration of their suitability for use in automotive situations as a means of detecting a collision. The basic building blocks of the models are based on simple visual receptive field interactions implemented on CNN-UM [5].

Finally I show another monocular collision warning method that efficiently approximates and can report on the so called time-to-contact variables belonging to different objects. Thus multiple separate warning signals are delivered in a parallel manner. Beside typical analogic image processing operations the method requires an efficient implementation of 'isotropic diffusion'. Thus, it is an excellent candidate for implementation on CNN-UM computers equipped with locally switchable - mask controlled- resistive grid feature.

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Methods used in the experiments

In the course of my work, theorems and assertions from the field of probability and statistics, methodologies related to neural activity modeling were used. The biological relevant modeling is based on neurophysiologic observations and measurements.

Algorithmic procedures requiring traditional computing methods were developed and tested in the MATLAB environment. Designed CNN templates and algorithmic procedures were tested on software simulators, such as the CANDY package and ALADDIN PRO 2.x[17], and on an industrial framework embedding different Cellular Visual Microprocessors: ACE4k[14],[15]. The simulators were developed in the Analogical and Neural Computing Laboratory. The implementation independent description of the developed methods was completed in different "CNN languages" (template, AMC, UMF, Alpha) ensuring their applicability on different hardware platforms. The design of the algorithm ensures that only nearest neighbor linear interaction operators (templates) required. Most of these are that can be tested on existing VLSI prototype systems[16].

The experiments and research efforts were interdisciplinary. A number of analyses were performed in a close cooperation with neurobiologists and engineers. In the evaluation of neurophysiologic recordings, observations and guidance of biologists supported the synthesis of theory and practical findings.

and the others whom I also wish a good luck. I owe a lot to Ms Katalin Keserű for her practical and official aid.

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It is hard to make a complete list of all those who I owe special thanks. I recall Dávid Bálya, Csaba Rekeczky, Ákos Zarándy, Károly László, László Orzó, István Szatmári, István Petrás, Gergely Timár, Mátyás Brendel

Main Results

In the following thesis I introduce a data-analytic method of multiple single neuron recordings for the determination of

- temporal scale of the neural activity
- different dynamical regimes, transient functional groups of neurons.

The method involves random and independent perturbation (or jitter) of each spike in a recorded train, using perturbations on the order of L milliseconds – via the technique described in the first thesis. The second step is to compute the value of some statistic on the surrogate, jittered train. Roughly, jittering the train should have the effect of preserving the coarse temporal structures of the trains (or those structures coarser than L milliseconds, such as, for example, spike counts measured in L millisecond intervals.) This leads to the following strategy for assessing the existence of fine temporal structure: repeating the jittering process many times, one can tabulate a distribution on the value of the statistic for jittered (surrogate) versions of the spike train, and then compare the value of the statistic on the original non-jittered spike train. If the original statistic is then atypical with respect to the jittered trains (for example, if it lies in a tail of the tabulated distribution), then one is led to suspect that the presence of fine temporal structure is necessary to account for the observed spike train. Specifically, one concludes that the data is incompatible with temporal structure that is (L-millisecond) coarse.

First thesis: assessment of temporal scale and patterns in multi neuron recordings

Ia Effective and biologically relevant surrogate data generation algorithm development and characterization

I proposed a computationally effective method for the generation of surrogate data from an original discretized bioelectric signal, typically multiple single neuron recordings. Original spikes of the neurons (spike times in X_0) are shifted randomly (with probability μ) and independently back and forth resulting in surrogate spike-trains:

- break
- fasten the seat belts
- preparation or use of air bags

The first method was adjusted and tested in small traffic and in the test driving area of the VOLVO car company within the framework of an international project called LOCUST.

Thesis II

Genetic algorithms might be useful in problem domains that have a complex fitness landscape as recombination is designed to move the population away from local minima that a traditional hill climbing algorithm might get stuck in. Particularly appropriate problems for genetic algorithms include timetabling, scheduling problems, automated design and I show that it can be effective in multi-dimensional (multi-channel) neural activity data analysis: here I test the performance and examine the suitability of analogic binary GA in connection with the analysis of fMRI data.

Thesis III

The application area of the developed collision warning systems is well defined: the primary targets are driving situations. The role of the system can be limited to give visual feedback on impending collisions or may initiate interventions at different levels:

- preparation of brakes

$$X_1' = X_1^0 + D = \left(x_1^0(1) + d_1, x_1^0(2) + d_2, \ldots, x_1^0(N) + d_N \right)$$

where the random variable d after I iterations can be characterized by the distribution (see Figure 1):

$$\eta_r(d = \delta, I) = \sum_{|\delta| \le v \le I/2, v \in \mathbb{N}} \mu^{2v-|\delta|} (1-\mu)^{I-(2v-|\delta|)} \binom{I/2}{v} \binom{I/2}{v-d}$$

The typical requirements for surrogate data is to preserve the main structure of the individual neuron activity records following changes in the firing rates (non-stationary) but disrupt fine interdependence between them. The most important features to preserve:

•total number of spikes

•non-stationarity; even sudden, transient changes in frequency

The technique can take physiological relevance and accuracy assumptions into account.

I discuss the role and possible significance of the parameters controlling the surrogate generation, and I also show a method for tuning them for optimal performance.

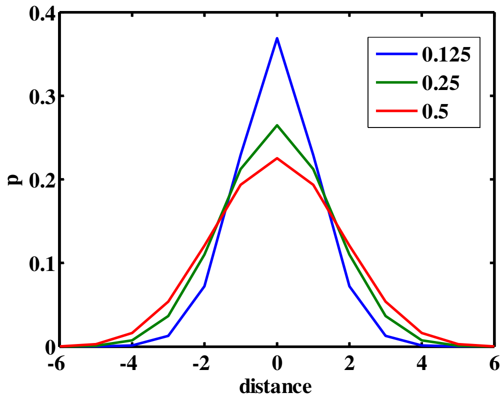


Figure 1 Profile of a single spike shift probability during random walk

Ib a bootstrap technique for finding and evaluating higher order temporal patterns in multi neuron recordings

I introduce a statistic that can be evaluated on original multiple single neuron recordings ($\mathbf{X}_0$) and their

implantation of electrodes in the scull the experimenter would like to see if the localization of the electrodes are optimal: whether the sites at they measure give rise to synchronization patterns expectedly.

Considering some future applications real-time processing and evaluation will be the minimum requirement: prediction and detection of epileptic seizures via intracranial electrodes are one of the task the generation and analysis of surrogate data may help.

Finally, the data exploration technique proposed in the thesis above has an ambitious – but not unrealistic – goal: recognition of important activity patterns seems to be a crucial step on the way of decoding the language of neurons, what in turn can ultimately be a synonym of "reading the mind". A fast, intelligent and reliable communication with the nervous system is the basis for advanced human-machine interfaces: on one hand, online translation of activity patterns may serve as a control signal for the actuators. On the other hand, sensory prosthesis have to "talk" to specific brain areas by means of sensible patterns.

Application Areas, experiments

Thesis I

The most trivial place of the statistical methods described here is at the offline analysis of simultaneous multi-electrode single-unit recording studies.

One example is shown here in the thesis: I studied multiple single-cell recordings from mammalian retinal ganglion-cells. The data was registered in the Friedrich Miescher Institute for Biomedical Research (Basel, Switzerland) by Dávid Bálya. A number of stimulus-locked and stimulus timing independent high order synchrony patterns were recognized and analyzed that traditional pair-wise correlation techniques could not detect. Evaluating the time scale of the non-stimulus locked patterns suggest that the accuracy of the coordination of certain retinal cells are in the milliseconds range.

In the preparation phase expensive and time consuming studies can benefit from quasi-realtime validation of the proper experimental setup. For example, before chronic

surrogates($\mathbf{X}_j$). The statistic calculate a statistic Z- counts all possible synchrony patterns - in the data:

$$Z_j = g\left(\mathbf{X}^j\right), 1 \le j \le J$$

Calculating the bootstrap significance of patterns based on their empirical distribution indicates if occurrence of a pattern is higher than expected by chance: decision about rejection of H_0 (there are only independent processes) can be made based on the statistical rank of the original Z_0 within the order statistics of Z. I show, that manipulating the parameters of the surrogate generation process one can

- defines extra limit
- Tell if the occurrence of a certain pattern is statistically significant, thus a functional transient cell group is formed
- Determine if there are transient formations of functional cell groups

Ic Implementation of the surrogate data generation on CNN-UM: an analogic approach

I found an effective solution for the CNN-UM architecture adaptation of the surrogate data generation method described in the first part of the thesis. The original algorithm is modified to be suitable for fast parallel computing. Emulating a certain type of cellular automata (CA) by the CNN-UM I was able to generate good quality pseudo-random patterns with controllable features that suit the needs of high throughput surrogate data generation. The algorithm was tested on an industrial framework embedding the ACE4k. Cellular Visual Microprocessor. Although the geometry of the chip (64 by 64 cells) is not ideal for that kind of computation, it could serve as a feasibility test-bed.

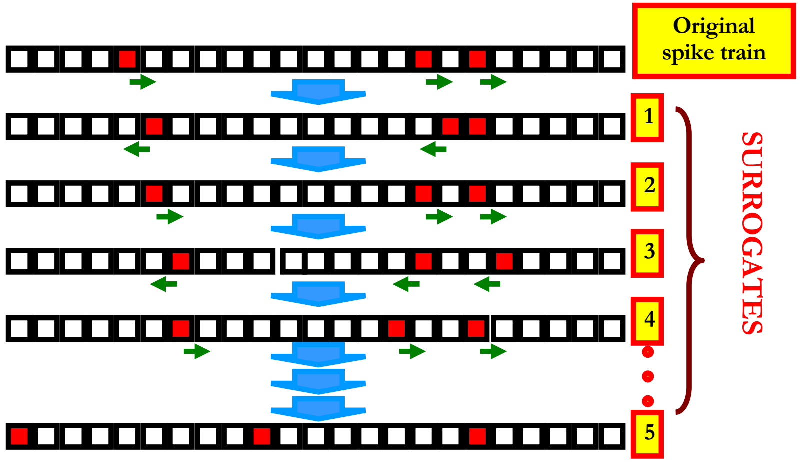
Where $m(i,j) \in \{0,1\}$ is the space-variant mask, or indicator function defining pixel (i,j) to be active or inactive.

time-to-contact variables belonging to different objects. Thus multiple separate warning signals are delivered in a parallel manner. The core principle is based on the optical law that the ratio between the area of a projected image of an object and its rate of change is linearly correlated with τ, the time-to-contact:

$$\tau = 2\frac{A_p(t)}{\dot{A}_p(t)}$$

Beside typical analogic image processing operations the method requires an efficient implementation of 'isotropic diffusion'. Thus, it is an excellent candidate for implementation on CNN-UM computers equipped with locally switchable - mask controlled- resistive grid feature. The required CNN dynamics can be characterized as:

$$\frac{d}{dt}x_{i,j}(t) = m(i,j)\left(-x_{i,j}(t) + \sum_{\substack{k,l\in N\\ k\neq 0, l\neq 0}} \frac{m(i+p,j+q)\,y_{i+k,j+l}(t)}{\sum_{\substack{p,q\in N\\ p\neq 0,q\neq 0}} m(i+p,j+q)}\right)$$



Second thesis: analogic implementation of a genetic algorithm

I proposed an analogic method for an efficient, scalable pseudorandom area selection within a CNN-UM array which enable the implementation of a special 'fine-grained' type genetic algorithm. The algorithm is based on a cellular automata (CA) rule that can generate pseudo-random black and white patterns[17]:

$$R_{i,j}(n+1)=(R_{i+1,j}(n) \text{ OR } R_{i,j+1}(n)) \text{ XOR } R_{i-1,j}(n) \text{ XOR } R_{i,j-1}(n) \text{ XOR } R_{i,j}(n)$$

I defined the optimal parameters for the method maximizing the probability that given an MxN array a single line can be selected and requiring the minimal number of iterations of the CA rule at the same time.

Third thesis: analogic algorithms for visual collision prediction

Thesis III/a Collision warning algorithm inspired by the locust visual system

I took part in the design of a biologically inspired collision prediction algorithm based on the visual system of the locust. I modified and completed the model to match the requirements of robust operation in real-world car driving situations. We implemented the algorithm on a real-time visual computing system and I adjusted and tested its sensitivity/specificity parameters in real driving scenarios. The system can differentiate between a limited number of object classes according to the need of robust collision warning: the method recognizes pedestrians and vehicles on an impending collision course, and warn reliably the driver 0.5-1 sec before the actual collision, with negligible amount of false alarms.

Thesis III/b An analogic algorithm for parallel multiple collision prediction based on isotropic diffusion.

I designed a monocular collision warning method that efficiently approximates and can report on the so called