INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team cortex

Neuromimetic Intelligence

Lorraine

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Activity Report

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1. Team

CORTEX is a project-team of the LORIA (UMR 7503) common to CNRS, INRIA, University Henri POINCARÉ *Nancy 1 (UHP), University Nancy 2 and National Polytechnic Institute of Lorraine.*

Head of project-team
Frédéric Alexandre [Research Director INRIA]

Administrative assistant
Martine Kuhlmann [CNRS, part time in the project-team]

Staff members (INRIA)
Nicolas Rougier [Research scientist]
Arnaud Tonnelier [Research scientist (from october 2003)]

Staff member (CNRS)
Dominique Martinez [Research scientist]

Staff members (Universities)
Yann Boniface [Teaching Assistant, U. Nancy 2]
Laurent Bougrain [Teaching Assistant, UHP]
Bernard Girau [Teaching Assistant, U. Nancy 2]
Jean-Charles Lamirel [Teaching Assistant, U. Strasbourg (on partial secondment at INRIA until september 2003)]

Ph. D. students
Shadi Al Shehabi [Syria]
Mohammed Attik [INRIA]
Khaled Ben Khalifa [Student intern]
Claudio Castellanos Sanchez [CONACYT-SFERE]
Nizar Kerkeni [Tunisia (half-time with Tunisia)]
Olivier Ménard [Supélec]
Olivier Rochel [UHP]
Georges Schutz [Luxembourg]
Julien Vitay [INRIA]

Post-doctoral fellows
Rémi Coulom [INRIA (from september 2003)]
Didier Fass [INRIA]
Etienne Hugues [ARC NOSE]
Bruno Scherrer [Teaching Assistant (until september 2003)]

Technical staff
Philippe Beylik [Junior technical staff (until september 2003)]
Guillaume Ferrier [Junior technical staff (from september 2003)]
Jean-Etienne Figard [Student intern]
François Parmentier [Project technical staff (until december 2003)]

Research scientist (Supélec)
Hervé Frezza-Buet [Teaching Assistant]

2. Overall Objectives

The goal of our research is to study the properties and capacities of automatic information processing, based on distributed, numerical, and adaptive algorithms and to show that such a kind of processing may allow to build “intelligent” systems, i.e. able to extract knowledge from data and to manipulate that knowledge to solve problems. More precisely, these studies rely on the elaboration and analysis of neuromimetic connectionist models (*cf.* § 3.1), developed along two sources of inspiration, computational neuroscience and machine learning.

These sources of inspiration are studied together because both are interested in better understanding how such distributed models can learn internal representations, and manipulate knowledge and both propose complementary approaches allowing cross-fertilization.

The domain of machine learning proposes connectionist numerical models for information processing in a statistical framework, to extract knowledge from data (*cf.* § 3.2). The domain of computational neuroscience proposes distributed theoretical models and elementary mechanisms that aim at explaining how the human or animal nervous system processes information at various levels, from perception to reasoning (*cf.* § 3.3).

Complementarily to our multidisciplinary domains of inspiration, our research is applied in domains like data and signal interpretation, intelligent sensors, robotics, and computer-aided decision. More generally, our models are dedicated to monitoring complex, multimodal processes, perceiving and acting on their environment (*cf.* § 4.1).

These models are firstly implemented on classical computers, but other architectures are also explored, namely parallel machines, autonomous robots, and more generally specialized circuits for embedded systems, as suggested by our applications (*cf.* § 3.5).

Several fundamental issues are also associated to our researches. **Emergence** is a phenomenon difficult to master in such an ascending, distributed approach, where programming is local, whereas the observed behavior is global, emerging from the interaction between numerous simple elements. **Autonomy** means that our systems have to learn their tasks without explicit *a priori* knowledge of the external world, where unexpected events can occur. **Learning** is therefore a good way to adapt to the changing world, and for complex tasks several kinds of memory have to be considered (short/long term, procedural/declarative, continuous/incremental). **Cognitive tasks** like reasoning, planning and knowledge extraction are not classical applications for neural networks and it is important to show how such problems can be solved by a distributed approach.

All these issues are studied in the four topics of research we are currently carrying out. (i) In computational neuroscience, at a behavioral level, we are developing models of cerebral neuronal structures (*cf.* § 6.1), to allow the navigation of autonomous robots. (ii) In computational neuroscience, at the neuronal level, we are modeling spiking neurons (*cf.* § 6.2), seen as dynamic systems with temporal behavior, allowing synchronization within populations of neurons. (iii) From a more statistical point of view, we are studying how classical continuous neuronal models can be adapted to database and signal interpretation, for knowledge extraction (*cf.* § 6.3). (iv) From a more technological point of view, all the above-mentioned models are adapted to allow implementations on dedicated architectures (*cf.* § 6.4).

3. Scientific Foundations

3.1. Connectionism

Key words: *connectionism*, *artificial neural network*, *perceptron*, *multi-layer perceptron*, *self-organizing map*.

Connectionism can be defined as the study of graphs of simple interconnected units, performing elementary numerical calculus, from their inputs and internal parameters. Particularly, neuro-inspired connectionism is interested in artificial neural networks, like perceptrons or self-organizing maps. These models have been deeply studied in the domain of machine learning for their properties of learning and approximation and their links with other statistical tools.

Artificial neural networks have been successfully applied to a variety of tasks (pattern matching, prediction, control) in a variety of domains (signal processing, industrial processes, medicine). Beyond the interest of computing statistics on databases from such domains, one can also wonder about using such capabilities for more cognitive tasks like interpretation and knowledge extraction, which are not classical properties of artificial neural networks, but are fundamental from an expertise point of view. Current research aims at extending their capabilities to these tasks (*cf.* § 3.2).

Other connectionist approaches aim at going back to the basis of connectionism and look for a tighter inspiration from neuroscience. The inspiration can be local and look for more realistic models of neuronal functioning and particularly of its dynamical aspect (*cf.* § 3.4). It can be global with the goal of implementing tasks related to the modeling of integrated behavior (*cf.* § 3.3). Both biologically inspired approaches are refered to as computational neuroscience. They are multidisciplinary and look for a better understanding of brain functioning (biological aspect) and neuronal computation, seen as a new way of computation (computer science aspect).

Another important issue in connectionism is to take benefit from the distributed parallel nature of its computations and to develop implementations that exploit that characteristics. Such implementations lead to cope with the real nature of neuronal computation, they may improve the performance of computation and be embedded in electronic devices (*cf.* § 3.5).

3.2. Intelligent information processing

Key words: *data analysis*, *pre-processing*, *neuro-symbolic integration*, *visualization*, *knowledge extraction*.

Artificial neural networks are information processing systems that can widely be applied to data mining. They present a lot of capabilities for analyzing and pre-processing data, as well as visualizing and extracting knowledge. These capabilities can be developed through unsupervised and supervised networks to obtain data analysis close to the one performed by statistical methods. To improve the performance of such information processing system, statistical or neuronal pre-processing can deal with missing data, redundancy information and outliers.

Networks with a minimal achitecture can be obtained using pruning algorithms. The operating procedure of the pruning methods is to remove, during learning, connections or neurons, or both, which have less influence on the system performance. Reducing the complexity of the networks prevents overtraining and allows easier implementation and knowledge extraction (selection of variables, rule extraction).

Another domain of research concerns multiscale approaches. When data are linked by a temporal or a geographical dimension, it is often important to be able to switch from a macroscopic point of view to a microscopic one and reciprocally, because some pieces of information are available only at one level and because staying at a high level of description reduces speed of processing. Using a multiscale description can also be useful to represent the interpreted information in a hierarchical way.

3.3. Computational neuroscience: behavioral approach

Key words: *computational neuroscience*, *cortical model*, *population of neurons*, *cortical column*, *behavioral model*.

In the behavioral approach of computational neuroscience, inspiration from neuroscience corresponds to defining and modeling the main information flows in the brain, together with the functional role of the main neuronal structures and their relation to some cognitive tasks.

The main cognitive tasks we are interested in are related to the autonomous navigation of a robot in an unknown environment (perception, sensorimotor coordination, planning). The corresponding neuronal structures we are modeling are part of the cortex (perceptive, associative, frontal maps) and the limbic system (hippocampus, amygdala, basal ganglia).

Corresponding models of these neuronal structures are defined at the level of the population of neurons and functioning and learning rules are built from neuroscience data to emulate the corresponding information processing (filtering in perceptive maps, multimodal association in associative maps, temporal organization of behavior in frontal maps, episodic memory in hippocampus, emotional conditioning in amygdala, selection of action in basal ganglia).

Our goal is to iteratively refine these models, implement them on autonomous robots and make them cooperate and exchange information, toward a completely adaptive, integrated and autonomous behavior.

3.4. Computational neuroscience: spiking neurons

Key words: *computational neuroscience, spiking neurons, synchronization of activity, olfaction, neural code*.

Computational neuroscience is interested in having more precise and realistic models of the neuron and especially of its dynamics. Compartmental models describe the neuron through various compartments (axon, synapse, cellular body) and coupled differential equations. Such models describe the activity of real neurons to a high degree of accuracy. However, because of their complexity, these models are difficult to understand and to analyze. For this reason our work focuses on the use of simplified models, i.e. simple phenomenological models of spiking neurons, that try to capture the dynamic behavior of the neuron in leaky integrators that explain how spikes can be emitted through time from input integration.

These models are interesting for several reasons. From a neuroscience point of view, they allow a better understanding of neuronal functioning. Indeed, although it is well known that real neurons communicate with spikes, i.e. a short electrical pulse called action potential, the precise nature of the neural code is a topic of intense debate. The firing-rate coding hypothesis stating that the firing frequency of a neuron estimated by temporal averaging encodes information is now challenged by a number of recent studies showing that precise spike timing is a significant element in neural encoding. In particular, stimulus-induced synchronization and oscillatory patterning of spike trains have been experimentally observed in perceptive systems like in vision or olfaction. Moreover, synchronization of neural activities seems to play a role in olfactory perception as, when it is pharmacologically abolished, honeybees do not discriminate anymore between similar odors.

From a computer science point of view, we investigate the spatio-temporal dynamics of simplified models of spiking networks using both mathematical analysis and numerical simulations. Therefore, we have to define (i) a tractable mathematical analysis with methods coming from the theory of nonlinear dynamical systems and (ii) an efficient computing scheme with either event-driven or time-driven simulation engines. These models can also be applied to difficult coding tasks for machine perception like vision and olfaction, and can help to understand how sensory information is encoded and processed by biological neural networks.

3.5. Connectionist parallelism

Key words: *connectionism, parallelism, MIMD computers, digital circuits, FPGA* .

Connectionist models, such as neural networks, are the first models of parallel computing. Artificial neural networks now stand as a possible alternative with respect to the standard computing model of current computers. The computing power of these connectionist models is based on a very fine-grain massive parallelism with densely interconnected computation units.

The connectionist paradigm is the foundation of the robust, adaptive, embeddable and autonomous models of processing that we develop in our team. Therefore their specific massive parallelism has to be fully exploited. Furthermore, we use this intrinsic parallelism as a guideline to develop new models and algorithms for which parallel implementations are naturally made easier.

Two main approaches are studied in our team. A coarse-grained approach focuses on neural functionalities. Its natural implementation device is a MIMD parallel computer. In this approach, we study and compare both neural network parallelism and general purpose computer parallelism in order to map artificial neural networks onto processors networks. This work provides many tools to develop distributed neural networks and to study the distributed properties of connectionist models : synchronization between neurons, synchronization between modules. Thanks to the use of MIMD parallel computers to implement our models, we may develop large models, i.e networks with a large amount of neurons and connections. We may use this possibility to study the emergence of properties from very large populations of neurons.

A second approach claims that the parallelism of connectionist models makes them able to deal with strong implementation and application constraints. This claim is based on both theoretical and practical properties of neural networks. It is related to a very fine grain of parallelism that fits parallel hardware devices, as well as to the emergence of very large reconfigurable systems that become able to handle both adaptability and massive parallelism of neural networks. More particularly, digital reconfigurable circuits (e.g. FPGA, Field

Programmable Gate Arrays) stand as the most suitable and flexible device for fully parallel implementations of neural models, according to numerous recent works in the connectionist community. We carry out various arithmetical and topological studies that are required by the implementation of several neural models onto FPGAs, as well as the definition of hardware-targeted neural models of parallel computation.

4. Application Domains

4.1. Overview

Key words: *signal interpretation*, *robotics*, *perception/action interaction*, *database interpretation*, *multidisciplinary applications*.

Our connectionist models are applied to two kinds of tasks. From a machine learning point of view, the idea is to combine the statistical exploration of databases with knowledge extraction from these databases. From a computational neuroscience point of view, we are interested in modeling various aspects of intelligent behavior. Domains of application are thus very wide since they include domains where databases have to be structured and interpreted and domains where perception-action loops have to be elaborated from the exploration of an unknown world.

Beyond the good performances of the neuronal paradigm on these tasks, these applications are also interesting for several reasons. From an expertise point of view, they allow to extract knowledge from databases including geographical and geological data (*cf.* § 8.2), industrial data (*cf.* § 8.3), bibliographical data (*cf.* § 8.3) or EEG signals (*cf.* § 8.3).

From a technological point of view, they allow to define a methodology for using artificial neural networks (*cf.* § 5) and they can lead to hardware implementation (*cf.* § 5.7). From a multidisciplinary point of view, they lead to projects (*cf.* § 8.2 and § 8.3) including partners from different domains and working together to the better understanding of the brain (neuroscientists, ethologists, physicians).

5. Software

5.1. Parallel neuronal library

Participants: Yann Boniface, Laurent Bougrain, Olivier Rochel.

Key words: *parallelism*, *MIMD*.

Artificial neural networks are known to be intrinsically parallel models. Moreover, they need large computation capabilities, especially for biologically inspired models. At the same time, parallel computer technologies get more accessible, in terms of availability as in terms of financial costs.

We have designed the HIBS library as a parallel simulator dedicated to artificial neural networks. This simulator aims at facilitating the development of neural networks models. It also allows the study of the parallel properties and the emergence capabilities of large populations of artificial neurons.

To build this simulator, we have studied and compared both neural network parallelism and general purpose computer parallelism. We have shown large differences between these forms of parallelism and proposed a solution to map the neural parallelism onto the computer parallelism. This tool allows connectionists to use an MIMD shared memory parallel computer without any specific knowledge about parallelism, to implement their model without any algorithmic modifications.

In its current form, the simulator is a function library in 'C' language. This simulator works on both sequential workstation computers and MIMD shared memory general purpose parallel computers.

This library is currently used by some other research teams (in Metz, Lyon, Strasbourg).

5.2. Spiking neural networks simulation

Participants: Etienne Hugues, Dominique Martinez, Olivier Rochel.

Key words: *spiking neurons*, *event-driven simulator*.

A spiking neuron is usually modeled as a differential equation describing the evolution over time of its membrane potential. Each time the voltage reaches a given threshold, a spike is sent to other neurons depending on the connectivity. A spiking neural network is then described as a system of coupled differential equations. For the simulation of such a network we have written two simulation engines using either (i) an event-driven approach or (ii) a time-driven approach. They are respectively more dedicated to the simulation of integrate-and-fire neurons or Hodgkin-Huxley neurons.

- The event-driven simulation engine [22] was developed in C++ by O. Rochel during his PhD thesis. It allows to achieve good performance in the simulation phase while maintaining a high level of flexibility and programmability in the modeling phase. A large class of spiking neurons can be used ranging from standard leaky integrate-and-fire neurons to more abstract neurons, e.g. defined as complex finite state machines.
- The time-driven simulator engine called SIRENE was written in C and developed during the NOSE project (*cf.* § 8.2) for the simulation of a model of the antennal lobe, the first structure of the insect olfactory system. This simulator engine can simulate any type of spiking neural network and is indeed more dedicated to the simulation of biologically detailed models of neurons —such as conductance-based neurons— and synapses. Its high flexibility allows the user to implement easily any type of neuronal or synaptic model and use the appropriate numerical integration routine (e.g. Runge-Kutta at given order).

5.3. Control of robots

Participants: Hervé Frezza-Buet, Nicolas Rougier, Julien Vitay.

Key words: *client-server application*, *remote control*.

The NONO library allows to design generic client-server applications and is mainly oriented toward the remote control of a robot. It allows to easily define both the client and server sides by encapsulating them in a unified object oriented approach. The robot can then be concurrently controled and consulted by means of shared resource objects corresponding to available physical devices on the robot.

5.4. Implementation of computational neuroscience models

Participants: Yann Boniface, Hervé Frezza-Buet, Nicolas Rougier, Julien Vitay.

Key words: *computational neuroscience*.

The GRUMPF computational model is made of several elementary computational units, each of them possessing its own state values, that can be linked together. Each unit is able to expose a set of public values that can be read by linked units. Time is discretized and at each timestep, units are able to synchronously or asynchronously update their activities. The main feature of the GRUMPF library is that units are evaluated in parallel without any additional programming effort from the designer. This is implemented using the ParCeL-6 library that underlies GRUMPF computations. Furthermore, computational and visualization parts are fully separated by means of the NONO library (*cf.* § 5.3) that allows graphical clients to display control and visualization from a network running on a distant server.

5.5. Decision-making platform

Participants: Mohammed Attik, Laurent Bougrain, Guillaume Ferrier, Jean-Etienne Figard, Nizar Kerkeni.

Key words: *decision-making*.

DynNet is a decision-making platform written in Java. It has been developed to simplify the development and use of neural networks in general and of dynamical architecture in particular. This platform is composed of three parts : a data importation and manipulation library, a neural networks library and a graphical user interface that integrates these tools into an application that handles every aspect of the decision-making process. As system requirements, any operating system that includes a Java Virtual Machine such as Microsoft Windows 98 and later, GNU/Linux, Solaris, MacOS are compatible operating systems. The software requires a configuration with Pentium III or equivalent and at least 256 MB of memory.

5.6. MicroNOMAD-MultiSOM

Participants: Shadi Al Shehabi, Jean-Charles Lamirel.

Key words: *knowledge discovery, documentary database*.

The MicroNOMAD-MultiSOM software mainly focuses on the automatic extraction and organization of knowledge that is embedded in documentary databases. The basic principle of this software is to provide users with interactive and interconnected cartographies of knowledge materializing several different syntheses of the content of a given documentary database. The underlying model of the MicroNOMAD-MultiSOM software represents an extension of Kohonen's SOM model to a multi-maps (i.e. multi-viewpoints) context. Due to the flexibility of this extension, the resulting maps can both play the role of elaborated browsing tools, data mining tools, as well as tools for assisting users in querying the documentary database. The model allows users to exploit dynamic exchange between the multiple viewpoints for highlighting correlations between the different views on the same data. It also permits the use of partial or incomplete descriptions of the data and accepts simultaneous representations of the same data with regard to different media. The MicroNOMAD-MultiSOM software has been used on different operational applications of data mining [18] (*cf.* § 8.3 and § 8.4). The versions 1 and 2 of this software have been patented by INRIA. The MicroNOMAD-MultiSOM software has been chosen as one of the two softwares of reference for analyzing Web data in the framework of the European EICSTES project (*cf.* § 8.3). The version 3 of this software that offers numerous extensions for analyzing unstructured data as well as numerous functions for the automation of analysis is currently finalized in the project. Many different analyses are currently conducted in the framework of EICSTES project thanks to the use of the MicroNOMAD-MultiSOM software.

5.7. Neural network synthesis on FPGA

Participants: Philippe Beylik, Bernard Girau.

Key words: *digital circuits, FPGA, parallelism*.

To date the majority of neural network implementations have been in software. Despite their generally recognised performances, the high cost of developing ASICs (Application Specific Integrated Circuits) has meant that only a small number of hardware neural-computing devices has gone beyond the research-prototype stage in the past. With the appearance of large, dense, highly parallel FPGA circuits, it has now become possible to realize large-scale neural networks in hardware, with the flexibility and low cost of software implementations.

Though easier than ASIC development, implementations of neural networks on FPGAs still require a significant amount of work, especially for connectionists who are not very familiar with such tools as the VHDL language, synthesis tools, etc. Therefore, we have begun to develop a generic methodology to fully automatically specify, parametrize and implement neural networks according to various application and technological constraints (e.g. area of targeted FPGAs, required precision, etc).

This project implies that we handle very different aspects: it starts from a state of the art and a critical analysis of existing solutions for the implementation of connectionist computations on reconfigurable circuits, it needs to determine and maximize the genericity of all already developed neural blocks, and it requires a precise analysis of the relations between application data, device specifications, and performances, for each valid technological solution.

6. New Results

6.1. Behavioral computational neuroscience

Participants: Frédéric Alexandre, Yann Boniface, Claudio Castellanos Sanchez, Rémi Coulom, Hervé Frezza-Buet, Olivier Ménard, Nicolas Rougier, Julien Vitay.

This section summarizes our recent results in the domain of modeling the cortex (visual features extraction, motion detection, multimodal association, visiomotor coordination) and other extra-cortical structures (amygdala).

6.1.1. Visiomotor coordination

In the domain of robotic, modeling the visiomotor axis is an important issue that we explore for various aims described in the European MirrorBot project (*cf.* § 8.3), the Robea CNRS project (*cf.* § 8.2) and the CPER (*cf.* § 8.1).

First, we have refined our models of visual perception, inspired from the architecture and processing in the visual tractus from the retina to the primary visual cortex through the lateral geniculate nucleus of the thalamus. In collaboration with Supélec-Metz, a dynamic library, lgn2v1, was provided, that leads to a distributed representation of the visual scene, robust to noise, allowing further processing in the cortex to be more linear and easier to compute. It is able to extract different features from an image, like contrast, edge orientation, color.

More generally, visiomotor transformations are the basic elements of the cognitive and motor behaviour of a robot. This step was studied extensively and permitted the use of redundant and distributed representations (such as our models of visual perception) which can be reused by others modules. They were applied to our Peoplebot robot which is now able to perform gaze centering and grasping tasks in a reactive way with a satisfying precision, and they were also applied to a robotic arm performing pointing tasks. These transformations are furthermore reversible, which means they can be used to predict the sensorial consequences of an action, either executed or imagined. This is capital for cognitive tasks requiring evaluation of an eventual reward depending on the action.

The underlying associative models have been developed to highlight several aspects like the estimation of an inverse model and its relation with the computation of a jacobian, the design of an original and cheap connectivity between the visual and motor information and the unsupervised self-organized learning of these two representations together with the associative visiomotor distributed representation [21].

6.1.2. Motion detection

Visual perception of motion is a major challenge in machine perception research, since it constitutes an important parameter in a wide variety of tasks such as path-finding, estimation of time to collision, perception of gestures, movement control, etc.

We are developing a bio-inspired neural architecture to detect, extract and segment the direction and speed components of the optical flow within sequences of images [5]. The structure of this model derives directly from the course of the optical flow in the human brain. It begins in the retina and receives various treatments at every stage of its magnocellular pathway through the thalamus and the cortex [13].

We have mainly focused on two fundamental problems in the treatment of a sequence of images. Firstly, the computation of their optical flow (a three-stage process: pre-processing based on filters, extraction of elementary characteristics and integration into a 2D optical flow), and secondly, the extraction of the egomotion. This work faces many concrete difficulties, such as specular effects, shadowing, texturing, occlusion and aperture problems. Moreover, the complexity of this task must be dealt with within the implementation constraint of real-time processing.

Our model mostly handles the properties of three cortical areas called V1, MT (middle temporal), and MST (middle superior temporal): the MT area detects patterns of movement, while spatio-temporal integration is made at the local level by V1 and at the global level by both MT and MST, so that a multi-level detection and integration may discriminate egomotion from movements of objects in a scene and from the scene itself.

Our first attempts have dealt mainly with manipulation of the optical flow by testing various spatio-temporal filters followed by neural processing based on shunting inhibitions. Current efforts are looking at the definition of a model of the magnocellular pathway for the detection of the movement of one or several objects in various dynamic scenes after egomotion extraction.

6.1.3. Multi-modal integration

In the context of the Ministry Grant “Integrative and computational neuroscience” (*cf.* § 8.2), we are working on the difficult problem of multi-modal integration. This phenomenon provides us with an integrated representation of the world and the different stimuli we perceive (sound, view, odor, etc.).

In this work, we began on a model developed at the Institut des Sciences Cognitives in Lyon. With a DEA student, we have built some new algorithms to code the integration layer (an associative layer) and to learn this integration. The first aim of this work is to focus on the on-line aspects of the learning. We have provided a continuous algorithm to learn the different perceived stimuli and their integration on the associative map.

6.2. Spiking neurons

Participants: Frédéric Alexandre, Yann Boniface, Bernard Girau, Etienne Hugues, Dominique Martinez, Olivier Rochel.

Our primary research in fine grain computational neuroscience (*cf.* § 3.4) is on understanding how sensory information is encoded and processed by biological neural networks. More specifically, during the past few years, our work focused on the insect olfactory system for the following two reasons :

- The insect olfactory system is one of the simplest perceptive system and thus one of the best understood. For example, in the antennal lobe, the first structure of the insect olfactory system, recent experimental data have shown that, in the presence of an olfactory stimulus, transient synchronization of a subset of neurons occurs during a particular oscillation of the network and that this subset change in time in an odor-specific manner (spatio-temporal coding).
- Understanding how sensory information is encoded and processed by the insect olfactory system could be highly beneficial for designing efficient electronic noses for which gas sensors are highly nonselective and respond to a wide variety of odors, as do the broadly tuned olfactory receptors in insects.

In order to understand the underlying mechanisms that generate such a spatio-temporal coding and to explore their computational capabilities, we have used both mathematical analysis and numerical simulations of simplified models of spiking networks. Starting from a biologically detailed model of the antennal lobe, we derived a simplified model. In contrast to the original model that consists of conductance-based type neurons and biologically detailed synapses, our model simply consists of one-variable neurons coupled via simple exponential synapses. Theoretical investigations, confirmed by simulations with the time-driven simulator engine SIRENE (*cf.* § 5.2), have allowed to understand why the network activity is oscillatory and, on the individual neuron level, to discover that during a particular oscillation some neurons robustly emit a spike at quite precise times. This individual behaviour has been found to be stimulus-specific, thus defining a real code of the stimulus. Furthermore, time has been found to increase the distance between the codes of two close stimuli.

These findings thus provide a direct input for designing data analysis methods for artificial electronic noses. However, it becomes necessary to adapt the model so as to interface it with real gas sensors. We then derived a more abstract spiking neural network, that has a lower complexity compatible with our applications in artificial olfaction, but can still capture the spatio-temporal coding of our former model. In addition, a very efficient event-driven simulation engine was developed by O. Rochel during his PhD thesis (*cf.* § 5.2) for simulating this more abstract model using sequential or parallel machines [22].

6.3. Data exploitation and interpretation

Participants: Frédéric Alexandre, Shadi Al Shehabi, Mohammed Attik, Yann Boniface, Laurent Bougrain, Hervé Frezza-Buet, Jean-Charles Lamirel, Bruno Scherrer, Georges Schutz.

This research aims at adapting classical models of connectionism (*cf.* § 3.1) to extend their use to data interpretation and knowledge extraction (*cf.* § 3.2).

From geographical information systems, in a collaboration with geologists (*cf.* § 8.2), we are currently studying how pruning algorithms can help in knowledge extraction from multilayer perceptrons [4]. From medical databases, in a collaboration with physicians in Nancy and Tunisia (*cf.* § 8.4), we have studied how self-organizing algorithms can indicate interesting hints to differentiate EEG signals for epileptic seizure prediction and vigilance state identification [11][26]. This latter application has also led to the implementation on FPGA of a portable system (*cf.* § 6.4). All these applications have been made possible by our DynNet software library (*cf.* § 5.5).

We have also studied the interpretation of databases including an important temporal aspect, namely databases of sensor signals of a very complicated industrial machine in the domain of steelmaking (*cf.* § 8.3). We have more particularly proposed an hybridization between self-organizing maps and dynamic time warping.

We have also completed a work to see common features between classical algorithms in reinforcement learning and connectionism [1][23].

Furthermore, the integration of the Palo Alto systemic theory of communication in the internal behaviour of an information retrieval/data mining system represents an original contribution of the research works of our team. This integration is particularly well adapted to the management of complex media like images. However, this approach implies the design of specific models for developing strong interaction capabilities with the user, as well as extended capabilities of adaptation to the context. An important example of such a model is the map conjunction model (i.e. the multicriteria classification model) that we have developed. This model, whose name is MicroNOMAD-MultiSOM, represents an important extension of the Kohonen SOM model (*cf.* § 5.6). The automatic deduction capabilities of the model represent a major advantage as compared to usual classification methods in the domain of data analysis. Hence, these latter methods do not permit the dynamical management of several viewpoints that can be considered as several different dimensions on the same information. We focused this year on the definition of evaluation criteria for measuring the quality of numerical classification. We search for criteria that can be both independent of the classification method and of the intrinsic dimension of the data to be classified [19]. These latter properties that are not satisfied by usual classification criteria, like variance, are mandatory for evaluating the result of classification performed on documentary data. Hence, documentary data have such a characteristic that each datum is individually defined in low size description spaces, with low overlapping of one datum with another. This situation led to global description space of important size but of low density for documentary data.

The methods we have set up permit us to perform objective comparisons between classification methods that are commonly used in documentary domain. These comparisons allow us to highlight the superiority of a viewpoint-oriented approach as compared to a global approach. They also allow us to highlight the superiority of the topographic based method, like SOM, Neural Gas or Growing Neural Gas as compared to concurrent methods [27]. Lastly, the criteria we have defined permit us to define a methodology or optimizing the number of classes of a documentary classification. We have also experienced this methodology for analyzing Web data provided by the EICSTES project (*cf.* § 8.3). The result of our comparison between topographic methods also highlights the superiority of Neural Gas as compared to other topographic methods, like SOM or Growing Neural Gas, for documentary information analysis. Hence, the Neural Gas method appeared to be the most stable one for information analysis which are conducted on a small number of classes when data are sparse, like documentary ones. Taking this result into account we are currently extending the Neural Gas model in order to adapt it to our multicriteria classification approach. Our new multi Gas approach also led us to focus on information visualisation techniques for representing relationships between classes initially defined in highly multidimensional spaces. Hence, one of our recent alleys of research consists in developing an hyperbolic visualisation model based on the definition of hierarchies of Gas classes.

The limitations of the numerical classification methods, like MicroNOMAD-MultiSOM, are related to the errors of interpretation that they may generate as soon as they are used without preliminary care by non-specialists for the precise analysis of a given domain. On their own side, symbolic methods when they are used for the same goal present the limitation to deliver too detailed and too complicated results. We have shown that it is possible to set up cooperation protocol between the two types of methods by defining equivalences between Galois lattices and topographic maps [20]. These equivalences permit the generation of an accurate hierarchical interpretation of the topographic maps, and conversely, the definition of focal entry points in the Galois lattice. We are pursuing our studies about the relationships that can exist between the two types of methods. Our goal is to make use of the Galois lattice as validation tools for the thematic deduction that are provided by the inter-map communication mechanism of the MultiSOM model. These last studies, as well as the ones concerning the theoretical validation of the MultiSOM model through its comparison with formal models, like probabilistic models, represent the subject of a PhD work.

6.4. Hardware implementations

Participants: Frédéric Alexandre, Khaled Ben Khalifa, Philippe Beylik, Yann Boniface, Laurent Bougrain, Claudio Castellanos Sanchez, Bernard Girau, Dominique Martinez, Olivier Rochel.

Three main axes appear in our study of connectionist parallelism in conjunction with reconfigurable digital hardware: new hardware-adapted frameworks of neural computation, dedicated embeddable implementations, and automatic neural synthesis on FPGAs.

Many neural implementations on FPGAs handle simplified neural computations. Furthermore, many efficient implementation methods (on ASICs, neuro-computers, etc) have to limit themselves to few well-fitted neural architectures [12][3]. An upstream work is preferable: neural computation paradigms may be defined to counterbalance the main implementation problems, and the use of such paradigms naturally leads to neural models that are more tolerant of hardware constraints. In this domain, our main contribution is the definition and application of the FPNA paradigm (Field Programmable Neural Array): this hardware-adapted framework of neural computation leads to powerful neural architectures that are easy to map onto FPGAs, by means of a simplified topology and an original data exchange scheme. This work is now mature and first works have been carried out to include it both in embedded low-power implementations and in the technological solutions that will be handled by our automatic neural synthesis tool.

In the field of dedicated embeddable neural implementations, we use our expertise in both neural networks and FPGAs so as to propose efficient implementations of applied neural networks on FPGAs. We handle neural models that are still in a research process as well as neural networks that are applied to concrete problems. For example, we implement spiking neural networks so as to estimate their potential efficiency as massively parallel embedded models, whereas such models still deserve great research efforts. We also have proposed an FPGA implementation for a neural network that discriminates vigilance states in humans from electroencephalographic (EEG) signals : it is based on a fully parallel architecture that uses serial operators, and its performances in terms of area, speed and especially power consumption are highly satisfactory (its target is a light, easy to wear system). These works will be published in 2004.

The third axis is the development of a generic synthesis tool to fully automatically specify, parameterize and implement neural networks on FPGAs. To date, we have defined, implemented and tested various neural blocks (from multilayer perceptrons to spiking neurons) on an FPGA-equipped reconfigurable board. Moreover, we have developed some preliminary software tools that already handle the automatic generation of VHDL code from a simple generic description of multilayer neural networks. This project still requires a huge amount of work.

We have also continued our work of connectionist implementation on parallel machines and have developed a new parallel library based on a deterministic event-driven simulation core that is well suited to take into account the asynchronous nature of the communication between spiking neurons. The simulation tools have been evaluated on two available hardware platforms : a cluster consisting of 8 dual-processor nodes, and a high-performance parallel machine of the SGI Origin 3000 series.

Finally, various applications of autonomous behavior have been implemented on our robotic platforms.

8. Other Grants and Activities

8.1. Regional initiatives

8.1.1. Collaboration with INIST

Participants: Jean-Charles Lamirel, François Parmentier.

The goal of this collaboration is to propose neural models for the creation of easily interpretable representations issued from very big documentary databases. The main characteristic of this problem is that the size of the data description space is important (large set of keywords), but it contains only a small number of representative examples. We firstly worked on the detection of the best data projection subspaces and we then pursued the extraction and the representation of concepts that provide a reliable interpretation of the database content. Other neural solutions we are working on are the ones that can be applied for detecting marginal documents or marginal tendencies in a very big documentary database. The approach we have proposed is based on the experimentation of different kinds of neural projectors implementing novelty detection functions. The domain of application of the solutions described above is the analysis of the relations between the different laboratories of the academic domain. Our study combines in a parallel way analysis of the content of the Web pages belonging to the academic institutions and the analysis of the hyperlinks that are embedded in these pages. The multi-viewpoint techniques we deal with not only allow us to highlight correlations between actors and research themes, but also inter-actor correlations and inter-thematic correlations. A second domain of our activity concerns the porting of the DILIB toolkit to the XML format. The DILIB toolkit is a library of function whose role is to facilitate the manipulation of documentary information. The first version of this library has been developed in INIST. The porting presents the advantage of permitting inter-operability between the library and the whole set of applications managing semi-structured data. It will also facilitate the management of Web data, enlarging the application field of our own data analysis approach.

8.1.2. Action Teleoperation and Intelligent Assistants of the CPER

Participants: Frédéric Alexandre, Hervé Frezza-Buet, Dominique Martinez, Nicolas Rougier, Julien Vitay.

In the framework of the Contrat de Plan Etat Région, we are contributing to the project Teleoperation and Intelligent Assistants, whose goal is to study, with local partners from schools of engineers and laboratory on Automation, systems for the monitoring of industrial processes. More specifically, our role is to develop a biologically inspired connectionist system for visual perception and to integrate it on an autonomous robot.

8.1.3. Action Computation, Networks, Graphics of the CPER

Participants: Frédéric Alexandre, Yann Boniface, Dominique Martinez, Olivier Rochel.

In the framework of the Contrat de Plan Etat Région, we are also contributing to the project Computation, Networks, Graphics and we are implementing our models on MIMD parallel machines, making use of the HIBS library (*cf.* § 5.1).

In order to simplify the simulation of large spiking neural networks, we have developed a complementary library, based on a different algorithmic approach. This new parallel library is based on a deterministic event-driven simulation core that is well suited to take into account the asynchronous nature of the communication between spiking neurons. It has been integrated in the software developed by O. Rochel during his PhD thesis (*cf.* § 5.2).

The simulation tools have been evaluated on two available hardware platforms : a cluster consisting of 8 dual-processor nodes, and a high-performance parallel machine of the SGI Origin 3000 series.

8.2. National initiatives

8.2.1. Exploitation of Geographical Information Systems

Participants: Frédéric Alexandre, Mohammed Attik, Laurent Bougrain.

Our collaboration with the BRGM (Bureau de recherches géologiques et minières) intends to demonstrate how neural networks can be used efficiently in a practical problem of mineral exploration, where general domain knowledge alone is insufficient to satisfactorily model the potential knowledge of deposit formation using the available information in continent-scale information systems. The BRGM is interested by the understanding of the formation of ore deposits (precious and base metals) and the contribution to the exploration and discovery of new occurrences using artificial neural networks and specially artificial neural networks which are able to construct a revised model for knowledge extraction [4].

8.2.2. INRIA New Investigation Grant NOSE

Participants: Frédéric Alexandre, Etienne Hugues, Dominique Martinez, Olivier Rochel.

The aim of this cooperative research initiative from INRIA is

- to develop a biologically inspired artificial neural network model for olfactory perception and
- to consider its implementation within a robotic framework.

The first aspect of this work consists in developing spiking neural network models for solving odor discrimination and localization problems for which classical (rate coding) neural networks are not satisfactory. The second aspect of this work is about the use of olfactory perception in an autonomous robot so as to mimic the animal behavior of tracking specific odors. Possible future applications could include the detection and localization of explosives or gas leaks in hostile environments or in public places.

In order to test if we can develop an autonomous olfactory robot we first have equipped a Koala robot with two gas sensor arrays and performed tracking experiments with the robot moving in an arena. To this aim, we have first derived efficient navigation laws specific to the task of finding a gas source in a turbulent environment [16]. Although this approach has shown encouraging results, it is still limited to the presence of a single odor in the environment and the use of a gas sensor sensitive to that odor. It is well known however that gas sensors are non-selective and respond to a wide variety of odors. Therefore, in an outdoor environment, the odor we would like to locate is likely to be mixed with interfering odors and the robot may locate a source that is different from the one pursued. Animals like insects have the ability of tracking a specific odor even when it is mixed with interfering odors as it often occurs in nature. In analogy with the non-selectivity of gas sensors, a biological olfactory receptor is not tuned to a specific odor and hence presents a lack of selectivity. Despite broadly tuned receptors, the olfactory system of insects and in particular its first stage, the antennal lobe, encodes an odor in a specific way. Understanding such a coding could be highly beneficial for designing artificial electronic noses.

Much experimental data and in particular the work of Laurent's group from Caltech have shown that subsets of synchronized neurons in the antennal lobe change in an odor-specific manner. Such a transient synchronization encoding scheme has already been reproduced and studied by means of a biologically detailed model of the insect antennal lobe (Bazhenov et al. 2001). However, because of the high degree of complexity of this model, many aspects of the coding remain insufficiently understood.

We therefore have developed a reduced computational spiking neural network model of the antennal lobe that lends itself to mathematical analysis and large scale simulations. In contrast to the model of (Bazhenov et al. 2001) that consists of conductance-based neurons and synapses, our model simply consists of single-variable neurons coupled via simple exponential synapses. This reduced complexity allows a more complete understanding of the underlying biological processing principles and thus provides a direct input for designing data analysis methods for artificial electronic noses —for example by adapting the model so as to interface it with gas sensors.

8.2.3. Interdisciplinary Program Cognition and Information Processing of the CNRS - Project Olfactive Aversion

Participant: Frédéric Alexandre.

In the framework of the project “Networks and mechanisms of learning: neurobiological and computational approaches of olfactive aversion in rats” of the Interdisciplinary Program “Cognition and Information Processing” of the CNRS, we are collaborating with the Cognitive Neuroscience Laboratory in Bordeaux and the Cognitive Sciences Institute in Lyon. This project aims at studying the modifications in olfactive signal processing in amygdala, cortex and hippocampus in aversive conditioning tasks. We are responsible of the modeling part, with emphasis on the underlying circuitry (network of structures) and the associated learning rules.

8.2.4. Interdisciplinary Program Cognition and Information Processing of the CNRS - Project electronic nose

Participants: Etienne Hugues, Dominique Martinez, Olivier Rochel.

The objective of this project is to develop a biologically detailed model of the olfactory bulb, the analog for mammals of the insect antennal lobe. This work is ongoing in collaboration with the Institut des Sciences Cognitives and the Laboratoire de Neurosciences et Olfaction in Lyon.

8.2.5. Project Robea of the CNRS - Learning of visiomotor transformations

Participants: Frédéric Alexandre, Hervé Frezza-Buet, Olivier Ménard, Nicolas Rougier, Julien Vitay.

This project, in collaboration with Supélec-Metz, INSERM-Paris and EDF-Chatou, aims at proposing a generic neuronal methodology inspired from the modular cortical architecture to learn complex visiomotor loops. It will be applied to manipulation, reaching and grasping tasks for complex robots.

8.2.6. Ministry Grant “Integrative and computational neuroscience”

Participants: Frédéric Alexandre, Yann Boniface, Dominique Martinez.

This interdisciplinary project entitled “Distributed models of spiking neural networks for multisensory integration” gathers different teams interested in mathematics, robotic, psychology, biology and computer science around a model designed for multi-modal integration. This model has been first developed by the team Connexionnisme et Modélisation Cognitive in the Institut des Sciences Cognitives in Lyon.

Our purpose is to study relations between the different modules (perceptive and associative modules) and the learning of theses relations. This work is based on spiking neurons, elementary neuromimetic models of neurons.

Properties of these classes of neurons allow us to study models of attention. We expect to build models which discriminate stimuli as a function of their role in attention. We will study attention properties in the modal pre-processing and in the integration processing in associative areas. We claim that these properties contribute to the integrated representation of the world.

8.2.7. Ministry Grant “New analytic methodologies and sensors” SAWCapt

Participants: Etienne Hugues, Dominique Martinez, Olivier Rochel.

Because of the simplicity and compactness of hardware implementation, spiking neurons are very appealing for addressing embedded systems for robotics or portable low-power smart sensors in vision or olfaction. The objective of the SAWCapt project is to develop a spiking neural network capable of solving the non-selectivity problem encountered in gas sensors and to consider its use for designing an electronic nose featuring small size and low cost of fabrication. This research project, in collaboration with the Laboratoire de Physique des Milieux Ionisés et Applications in Nancy, will develop and broaden knowledge in both software implementation of olfactory neuromorphic systems and pattern recognition algorithms as well as hardware implementation of smart sensing applied to an electronic nose.

8.2.8. Ministry Grant Cognitique-Action :Affordances and man-machine interaction: an approach of aesthetics of interaction

Participant: Didier Fass.

This multidisciplinary project aims at studying and developing models for predictable design of affordances in man machine interaction. Affordance refers to the actionable properties between the real or artefactual world and an actor in the dynamics of interaction. We use knowledge and methods of both cognitive sciences and engineering and principles and rules of artistic communication and design applied to interaction design. Our partners are EURISCO International, a company specialized in cognitive engineering and aeronautics, and the electronic communication department of the Ecole Nationale Supérieure d'Art de Nancy.

8.2.9. CNRS Specific Action: Perceptive supply and interface

Participants: Didier Fass, Hervé Frezza-Buet, Nicolas Rougier.

The aim of the "Perceptive supply and interface" project is to set up a theorical ergonomy of assisting devices for people with perceptive disabilities. This theorical ergonomy must provide an explanation of how the technical design and appropriation of the coupling interfaces make possible cognitive activities. The constitutions of new percepts are analyzed and formalized taking into account handable properties from the perceptive supply interfaces. This is also compared with the coupling modalities of other artefacts like robots. Here pluridisciplinarity is a necessity. Cognitive sciences, ergonomy, interface engineering, robotic, philosophy of the technics and anthropology are combined. The laboratories involved in this specific action of the CNRS STIC department are : Costech/BIM (E.A. 2223/UMR 6600, Compiègne), ETIS (Upress-A 8051, Cergy), Institut de Sciences Cognitives (UMR 5015, Lyon), Neurophysique et Physiologie du Système Moteur (FRE 2361, Paris V), Laboratoire de Psychologie Expérimentale (UMR 8581, ParisV), Préhistoire et Technique (UMR 7055, ParisX) and Psy.Co (E.A. 1780, Rouen)

8.2.10. Convention with the Museum of La Villette

Participant: Jean-Charles Lamirel.

This project deals with intelligent access to the collections of the museum, with the interest to multiply user's views on these collections and also to led historians and administrators to discover unexpected links between the objects exposed in the collections. The central idea we apply for that goal is the coupling of two different classification methods both for visualizing the collection of objects, for constructing viewpoints on these objects, for constructing object subsets with variable level of granularity, and lastly for highlighting correlation between some of the properties of the objects. This approach represents a collaboration between the Cortex team and the Orpailleur team who deals with the Galois lattice classification technique.

The work of this year consisted in implementing the multicriteria classification approach on 3-dimensional representations of the object of the collections. The goal of this new approach is to dynamically highlight relation between the objects depending on the current view a user has of an object at a given time.

8.3. European initiatives

8.3.1. Project IST MirrorBot

Participants: Frédéric Alexandre, Hervé Frezza-Buet, Olivier Ménard, Nicolas Rougier, Julien Vitay.

This project from the European initiative FET (Future Emergent Technology) gathers INRIA-Lorraine, Sunderland University, Parma University, Ulm University and the Cognition and Brain Sciences Unit in Cambridge. Its main topic is biologically inspired multimodal neuronal learning for an autonomous robot acting on, perceiving, and representing the world [10].

8.3.2. Control of industrial machines

Participants: Frédéric Alexandre, Georges Schutz.

We are sub-contractor of a ECSC european project that gathers steelmakers from Luxembourg, Belgium and Spain. Its goal is to improve the control of an electric arc furnace by modeling the process. Our team is in charge of the neuronal modeling. A hybrid model from dynamic time warping and neuronal non-supervised models has been proposed to extract robust prototypes from data, which are temporal sequences of events.

8.3.3. IST Project EICSTES

Participants: Jean-Charles Lamirel, Shadi Al Shehabi.

The goal of this project is to set up both indicators and methods for the analysis of the Web data. The data that are managed in the framework of the project concern the Web pages of the institutional Web sites as well as the log files associated to the different servers and services provided by the institutions. The project covers a large scope of competence because it enhances collaborations between statisticians, social scientists and computer scientists. The MicroNOMAD-MultiSOM method (*cf.* § 5.6) is one of the two reference methods of the project [28]. After increasing the genericity of MicroNOMAD-MultiSOM method in order to adapt it to the context of the project, we have shown that it is particularly adapted for data analysis based on the textual content of Web pages. We are currently working with social scientists in order to relate the results of co-links analysis obtained with the other reference method of the project with the results of thematic analysis obtained by our method. A second task we are participating in this project is to establish a state of the art of the different methods of visualisation that are available for the information analysts. The panel of studied methods should be large and therefore not only concern neural methods. This large scope work is currently carried out and should lead to the publication of a reference book before the end of the year 2004.

8.3.4. IST Project Scholnet

Participant: Jean-Charles Lamirel.

The goal of the SCHOLNET project was to define a core environment for the development of a distributed digital multimedia library dedicated to academic usage. The resulting library was not only intended to provide usual services for accessing to distant textual information, like scientific papers, but also to provide services for accessing to distant non textual information as images and videos. Moreover, the aim was also to provide complementary services like multimedia annotation, multilingual information retrieval and personalized information filtering. The SCHOLNET project extended the environment based on the DIENST operational protocol proposed by the former ETDRL European project. Yet, this latter project only dealt with access to textual information distributed among different academic institutions. Our role in the SCHOLNET project was to propose a unified representation of the video documents, as well as elaborated methods for access to these documents. We also had a role in the construction of the user's profiles, as well as in the conception of the personalized information filtering services. We finally played a role in the evaluation of the final prototype and in the dissemination of information on the project results. The SCHOLNET project started in November 2000. The final version of the prototype as well as its preliminary evaluation has been successfully presented to the European commission in February 2003. The final report of the project has been delivered to the commission and has been approved in April 2003.

8.4. International cooperation

8.4.1. Project STIC with Tunisia

Participants: Frédéric Alexandre, Khaled Ben Khalifa, Laurent Bougrain, Bernard Girau, Nizar Kerkeni.

We are working with the faculty of medicine in Monastir on physiological signal interpretation (EEG, EMG, EOG). On the one hand, we have developed a connectionist system able to discriminate vigilance states with a good accuracy [11][26]. This system has been implemented on an FPGA, to get a light and easy-to-wear system. On the other hand, we are working with physiologist physicians to better understand sleep and associated pathologies.

8.4.2. Joint venture INRIA-NSC Taiwan

Participant: Jean-Charles Lamirel.

The domain of application of this project is a multimedia digital library including both text and images that can be accessed on-line on the Internet. The goal of the final project is to offer extended querying functionalities including query by keywords as well as query by example. The constraints for incrementally adding new documents, text or images, to the original database must be also taken into account. In this project, another constraint of the chosen approach is to deliver realistic computation time. Our approach is both based on the MicroNOMAD-MultiSOM model and on the methods of similarity computation in the highly multidimensional spaces developed in our team. We have proposed a first theoretical model of our approach. We are currently working on the operational implementation of the model.

9. Dissemination

9.1. Leadership within the scientific community

- Head of the Network Grand-Est for Cognitive Science; member of the piloting committee of the CNRS UMS RISC (F. Alexandre)
- Reviewing for journals : International Journal of Neural Systems, TSI (F. Alexandre), Journal of VLSI Signal Processing Systems (B. Girau)
- Reviewing for conferences : IJCAI (L. Bougrain)
- Organization of the workshop “A multidisciplinary approach to the study of frontal cortex”, Nancy Convention Centre, oct. 20 (N. Rougier, J. Vitay, F. ALexandre)
- Organization of the workshop “Information visualization” at LORIA, feb. 19 (D. Fass, J.-C. Lamirel, F. Alexandre)
- Organization of a special session on Web Mining, Orlando, July 2003 (J.-C. Lamirel)
- Member of the program committee of the International Conference on Machine Learning and Cybernetics 2003, Xi-an, China (F. Alexandre)
- Invited talk at the workshop “Anticipation”, Strasbourg, nov. 19-21 (F. Alexandre).
- Invited talk at the NATO Advanced Research Workshop (ARW) on electronic noses/sensors for detection of explosives, oct. 1-3, Coventry, UK (D. Martinez).

9.2. Teaching

- Courses given at different levels (DEA, DESS, IUT, Licence-Maîtrise) in computer science in Nancy and Strasbourg by most team members;
- Courses at the Master in Neuroscience in Strasbourg and in Cognitive Sciences in Lyon (F. Alexandre);
- Member of PhD defense committees (F. Alexandre, D. Martinez, J.C. Lamirel);
- Co-supervision of PhD in Tunisia (J.-C. Lamirel, F. Alexandre).

9.3. Miscellaneous

- First Prize of Research for the Lorraine Region in 2003 (F. Alexandre);
- Popularization activities to heighten school-boy awareness of scientific and technological studies (F. Alexandre);

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