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Project-Team CORTEX

Neuromimetic intelligence

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RESEARCH CENTER
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THEME
Computational Medicine and Neurosciences

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Project-Team CORTEX

Keywords: Computational Neurosciences, Signal Processing, Neural Network, Machine Learning, Brain Computer Interface

Creation of the Project-Team: January 01, 1997 , *Updated into Team:* January 01, 2013 .

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2. Overall Objectives

2.1. Introduction

The goal of our research is to study the properties and computational capacities of distributed, numerical and adaptative networks, as observed in neuronal systems. In this context, we aim to understand how complex high level properties may emerge from such complex systems including their dynamical aspects. In close reference to our domain of inspiration, Neuroscience, this study is carried out at three scales, namely neurons, population and behavior.

1. **Neurons:** At the microscopic level, our approach relies on precise and realistic models of neurons and of the related dynamics, analyzing the neural code in small networks of spiking neurons (*cf.* § 3.2).
2. **Population of neurons:** At the mesoscopic level, the characteristics of a local circuit are integrated in a high level unit of computation, i.e. a dynamic neural field (*cf.* § 3.3). This level of description allows us to study larger neuronal systems, such as cerebral maps, as observed in sensori-motor loops.
3. **Higher level functions:** At the macroscopic level, the analysis of physiological signals and psychometric data is to be linked to more cognitive and behavioral hints. This is for instance the case with electroencephalographic (EEG) recordings, allowing to measure brain activity, including in brain computer interface paradigms (*cf.* § 3.4).

Very importantly, these levels are not studied independently and we target progresses at the interface between levels. The microscopic/mesoscopic interface is the place to consider both the analog and asynchronous/event-based mechanisms and derive computational principles coherent across scales. The mesoscopic/macroscopic interface is the place to understand the emergence of functions from local computations, by means of information flow analysis and study of interactions.

Learning is a central issue at each level. At the microscopic level, the pre/post synaptic interactions are studied in, e.g., the framework of Spike Time Dependent Plasticity (STDP). At the mesoscopic level, spatial and temporal patterns of activity in neural population are the cues to be memorized (e.g. via the BCM rule). At the macroscopic level, behavioral skills are acquired along time, through incremental strategies, e.g. using conditioning, unsupervised or reinforcement learning.

Our research is linked to several scientific domains (*cf.* § 3.1). In the domain of computer science, we generate novel paradigms of distributed spatial computation and we aim at explaining their properties, intrinsic (e.g. robustness) as well as functional (e.g. self-organization). In the domain of cognitive science, our models are used to emulate various functions (e.g. attention, memory, sensori-motor coordination) which are consequently fully explained by purely distributed asynchronous computations. In the domain of neuroscience, we share with biologists, not only data analysis, but also frameworks for the validation of biological and computational assumptions in order to validate or falsify existing models. This is the best way to increase knowledge and improve methods in both fields.

In order to really explore such bio-inspired computations, the key point is to remain consistent with biological and ecological constraints. Among computational constraints, computations have to be really distributed, without central clock or common memory. The emerging cognition has to be situated (*cf.* § 3.6), i.e. resulting from a real interaction in the long term with the environment. As a consequence, our models are particularly well validated with parallel architectures of computations (e.g. FPGA, clusters, *cf.* § 3.5) and embodied in systems (robots) that interact with their environment (*cf.* § 3.6).

Accordingly, four topics of research have been carried out this year.

- Microscopic level (*cf.* § 6.1): neural code; time coding and synchronization; simulation; application to olfaction.
- Mesoscopic level (*cf.* § 6.2): motion perception; visual attention; motor anticipation; neural field implementation.
- Macroscopic level (*cf.* § 6.3): neural information processing; brain computer interface.

with a transversal topic related to:

- Embodied and embedded systems (*cf.* § 6.4): dedicated architectures.

It must be mentioned that Frédéric Alexandre, Nicolas Rougier and Thierry Viéville have moved to a new team, Mnemosyne (Inria Bordeaux), from September 2012. Of course, several research aspects (and publications) are thus shared between both teams.

2.2. Highlights of the Year

We designed a computational model of the primary somatosensory cortex that is able to develop topographic maps, maintain and reorganize them in the face of lesions. We used neural fields as a mathematical and computational framework and focused on area 3b innervated by hand mechanoreceptors. The combination of such neural field with a simple Hebbian/anti-Hebbian like learning rule advocates for an unsupervised, distributed, robust and biologically plausible model of a (simplified) somatosensory cortical model where thalamocortical connections are the main sites of plasticity. The major finding of our model is that a topographic map can emerge as a consequence of the interaction between thalamus and cortical excitatory afferent connections. These results were recently published in PLoS ONE [6].

3. Scientific Foundations

3.1. Computational neuroscience

With regards to the progress that has been made in anatomy, neurobiology, physiology, imaging, and behavioral studies, computational neuroscience offers a unique interdisciplinary cooperation between experimental and clinical neuroscientists, physicists, mathematicians and computer scientists. It combines experiments with data analysis and functional models with computer simulation on the basis of strong theoretical concepts and aims at understanding mechanisms that underlie neural processes such as perception, action, learning, memory or cognition.

Today, computational models are able to offer new approaches for the understanding of the complex relations between the structural and the functional level of the brain, thanks to models built at several levels of description. In very precise models, a neuron can be divided in several compartments and its dynamics can be described by a system of differential equations. The spiking neuron approach (*cf.* § 3.2) proposes to define simpler models concentrated on the prediction of the most important events for neurons, the emission of spikes. This allows to compute networks of neurons and to study the neural code with event-driven computations.

Larger neuronal systems are considered when the unit of computation is defined at the level of the population of neurons and when rate coding and/or correlations are supposed to bring enough information. Studying Dynamic Neural Fields (*cf.* § 3.3) consequently lays emphasis on information flows between populations of neurons (feed-forward, feed-back, lateral connectivity) and is well adapted to defining high-level behavioral capabilities related for example to visuomotor coordination.

Furthermore, these computational models and methods have strong implications for other sciences (e.g. computer science, cognitive science, neuroscience) and applications (e.g. robots, cognitive prosthesis) as well (*cf.* § 4.1). In computer science, they promote original modes of distributed computation (*cf.* § 3.5); in cognitive science, they have to be related to current theories of cognition (*cf.* § 3.6); in neuroscience, their predictions have to be related to observed behaviors and measured brain signals (*cf.* § 3.4).

3.2. Computational neuroscience at the microscopic level: spiking neurons and networks

Computational neuroscience is also interested in having more precise and realistic models of the neuron and especially of its dynamics. We consider that the latter aspect cannot be treated at the single unit level only; it is also necessary to consider interactions between neurons at the microscopic scale.

On one hand, compartmental models describe the neuron at the inner scale, through various compartments (axon, synapse, cellular body) and coupled differential equations, allowing to numerically predict the neural activity at a high degree of accuracy. This, however, is intractable if analytic properties are to be derived, or if neural assemblies are considered. We thus focus on phenomenological punctual models of spiking neurons, in order to capture the dynamic behavior of the neuron isolated or inside a network. Generalized conductance based leaky integrate and fire neurons (emitting action potential, i.e. spike, from input integration) or simplified instantiations are considered in our group.

On the other hand, one central issue is to better understand the precise nature of the neural code. From rate coding (the classical assumption that information is mainly conveyed by the firing frequency of neurons) to less explored assumptions such as high-order statistics, time coding (the idea that information is encoded in the firing time of neurons) or synchronization aspects. At the biological level, a fundamental example is the synchronization of neural activities, which seems to play a role in, e.g., olfactory perception: it has been observed that abolishing synchronization suppresses the odor discrimination capability. At the computational level, recent theoretical results show that the neural code is embedded in periodic firing patterns, while, more generally, we focus on tractable mathematical analysis methods coming from the theory of nonlinear dynamical systems.

For both biological simulations and computer science emerging paradigms, the rigorous simulation of large neural assemblies is a central issue. Our group is at the origin, up to our best knowledge, of the most efficient event-based neural network simulator (Mvaspike), based on well-founded discrete event dynamic systems theory, and now extended to other simulation paradigms, thus offering the capability to push the state of the art on this topic.

3.3. Computational neuroscience at the mesoscopic level: dynamic neural field

Our research activities in the domain of computational neurosciences are also interested in the understanding of higher brain functions using both computational models and robotics. These models are grounded on a computational paradigm that is directly inspired by several brain studies converging on a distributed, asynchronous, numerical and adaptive processing of information and the continuum neural field theory (CNFT) provides the theoretical framework to design models of population of neurons.

This mesoscopic approach underlines the fact that the number of neurons is very high, even in a small part of tissue, and proposes to study neuronal models in a continuum limit where space is continuous and main variables correspond to synaptic activity or firing rates in population of neurons. This formalism is particularly interesting because the dynamic behavior of a large piece of neuronal tissue can be studied with differential equations that can integrate spatial (lateral connectivity) and temporal (speed of propagation) characteristics and display such interesting behavior as pattern formation, travelling waves, bumps, etc.

The main cognitive tasks we are currently interested in are related to sensorimotor systems in interaction with the environment (perception, 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 aim 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. Brain Signal Processing

The observation of brain activity and its analysis with appropriate data analysis techniques allow to extract properties of underlying neural activity and to better understand high level functions. This study needs to investigate and integrate, in a single trial, information spread in several cortical areas and available at different scales (MUA, LFP, ECoG, EEG).

One major problem is how to be able to deal with the variability between trials. Thus, it is necessary to develop robust techniques based on stable features. Specific modeling techniques should be able to extract features investigating the time domain and the frequency domain. In the time domain, template-based unsupervised models allows to extract graphic-elements. Both the average technique to obtain the templates and the distance used to match the signal with the templates are important, even when the signal has a strong distorted shape. The study of spike synchrony is also an important challenge. In the frequency domain, features such as phases, frequency bands and amplitudes contain different pieces of information that should be properly identified using variable selection techniques. In both cases, compression techniques such as PCA or ICA can reduce the fluctuations of the cortical signal. Then, the designed models have to be able to track the dynamic evolution of these features over the time.

Another problem is how to integrate information spreading in different areas and relate this information in a proper time window of synchronization to behavior. For example, feedbacks are known to be very important to better understand the closed-loop control of a hand grasping movement. However, from the preparatory signal and the execution of the movement to the visual and somatosensory feedbacks, there is a delay. It is thus necessary to use stable features to build a mapping between areas using supervised models taking into account a time window shift.

Several recoding techniques are taken into account, providing different kinds of information. Some of them provide very local information such as multiunit activities (MUA) and local field potential (LFP) in one or several well-chosen cortical areas. Other ones provide global information about close regions such as electrocorticography (ECoG) or the whole scalp such as electroencephalography (EEG). If surface electrodes allow to easily obtain brain imaging, it is more and more necessary to better investigate the neural code.

3.5. Connectionist parallelism

Connectionist models, such as neural networks, are among 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 their distributed properties: a very fine-grain massive parallelism with densely interconnected computation units.

The connectionist paradigm is the foundation of the robust, adaptive, embeddable and autonomous processings that we aim at developing 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.

Our 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 parallelism grain 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 low cost fully parallel implementations of neural models, according to numerous recent studies 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-targetted neural models of parallel computation.

This research field has evolved within our team by merging with our activities in behavioral computational neuroscience. Taking advantage of the ability of the neural paradigm to cope with strong constraints, as well as taking advantage of the highly complex cognitive tasks that our behavioral models may perform, a new research line has emerged that aims at defining a specific kind of brain-inspired hardware based on modular and extensive resources that are capable of self-organization and self-recruitment through learning when they are assembled within a perception-action loop.

3.6. The embodiment of cognition

Recent theories from cognitive science stress that human cognition emerges from the interactions of the body with the surrounding world. Through motor actions, the body can orient toward objects to better perceive and analyze them. The analysis is performed on the basis of physical measurements and more or less elaborated emotional reactions of the body, generated by the stimuli. This elicits other orientation activities of the body (approach and grasping or avoidance). This elementary behavior is made possible by the capacity, at the cerebral level, to coordinate the perceptive representation of the outer world (including the perception of the body itself) with the behavioral repertoire that it generates either on the physical body (external actions) or on a more internal aspect (emotions, motivations, decisions). In both cases, this capacity of coordination is acquired from experience and interaction with the environment.

The theory of the situatedness of cognition proposes to minimize representational contents (opposite to complex and hierarchical representations) and privileges simple strategies, more directly coupling perception and action and more efficient to react quickly in the changing environment.

A key aspect of this theory of intelligence is the Gibsonian notion of affordance: perception is not a passive process and, depending on the current task, objects are discriminated as possible "tools" that could be used to interact and act in the environment. Whereas a scene full of details can be memorized in very different and costly ways, a task-dependent description is a very economical way that implies minimal storage requirements. Hence, remembering becomes a constructive process.

For example with such a strategy, the organism can keep track of relevant visual targets in the environment by only storing the movement of the eye necessary to foveate them. We do not memorize details of the objects but we know which eye movement to perform to get them: The world itself is considered as an external memory.

Our agreement to this theory has several implications for our methodology of work. In this view, learning emerges from sensorimotor loops and a real body interacting with a real environment are important characteristics for a learning protocol. Also, in this view, the quality of memory (a flexible representation) is preferred to the quantity of memory.

4. Application Domains

4.1. Overview

Our application domain is twofold:

On one hand, neuro-scientists are end-users of our researches. Data analysis is one issue, but the main outcomes concern modeling, namely the validation of biological assumptions either at a theoretical level or via numerical experiments and simulation of bio-processes. This includes algorithmic expertises and dedicated softwares.

On the other hand, science and technology of information processing is impacted. This concerns embedded systems such as in-silico implementations of bio-inspired processes, focusing on spatial and distributed computing. This also concerns embodied systems such as robotic implementation of sensori-motor loops, the bio-inspiration yielding such interesting properties as adaptivity and robustness.

5. Software

5.1. Spiking neural networks simulation

Participants: Dominique Martinez, Yann Boniface.

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 : (i) Mvaspike based on an event-driven approach and (ii) sirene based on a time-driven approach.

- Mvaspike : The event-driven simulation engine was developed in C++ and is available on http://mvaspike.gforge.inria.fr. Mvaspike is a general event-driven purpose tool aimed at modeling and simulating large, complex networks of biological neural networks. 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.
- Sirene : The time-driven simulator engine was written in C and is available on http://sirene.gforge.inria.fr. It has been developed for 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).

5.2. DANA: Implementation of computational neuroscience mechanisms

Participants: Nicolas Rougier, Mathieu Lefort, Wahiba Taouali.

Computational neuroscience is a vast domain of research going from the very precise modeling of a single spiking neuron, taking into account ion channels and/or dendrites spatial geometry up to the modeling of very large assemblies of simplified neurons that are able to give account of complex cognitive functions. DANA attempts to address this latter modeling activity by offering a Python computing framework for the design of very large assemblies of neurons using numerical and distributed computations. However, there does not exist something as a unified model of neuron: if the formal neuron has been established some sixty years ago, there exists today a myriad of different neuron models that can be used within an architecture. Some of them are very close to the original definition while some others tend to refine it by providing extra parameters or variables to the model in order to take into account the great variability of biological neurons. DANA makes the assumption that a neuron is essentially a set of numerical values that can vary over time due to the influence of other neurons and learning. DANA aims at providing a constrained and consistent Python framework that guarantee this definition to be enforced anywhere in the model, i.e., no symbol, no homonculus, no central executive.

5.3. ENAS: Event Neural Assembly Simulation

Participants: Frédéric Alexandre, Axel Hutt, Nicolas Rougier, Thierry Viéville.

EnaS (that stands for “Event Neural Assembly Simulation”) is a middleware implementing our last numerical and theoretical developments, allowing to simulate and analyze so called "event neural assemblies". The recent achievements include (in collaboration with the Neuromathcomp EPI): spike trains statistical analysis via Gibbs distributions, spiking network programing for exact event’s sequence restitution, discrete neural field parameters algorithmic adjustments and time-constrained event-based network simulation reconciling clock and event based simulation methods. It has been designed as plug-in for our simulators (e.g. DANA or Mvaspike) as other existing simulators (via the NeuralEnsemble meta-simulation platform) and additional modules for computations with neural unit assembly on standard platforms (e.g. Python or the Scilab platform).

5.4. OpenViBE

Participants: Laurent Bougrain, Octave Boussaton.

OpenViBE is a C++ open-source software devoted to the design, test and use of Brain-Computer Interfaces. The OpenViBE platform consists of a set of software modules that can be integrated easily and efficiently to design BCI applications. Key features of the platform are its modularity, its high-performance, its portability, its multiple-users facilities and its connection with high-end/Virtual Reality displays. The “designer” of the platform enables to build complete scenarios based on existing software modules using a dedicated graphical language and a simple Graphical User Interface (GUI). This software is available on the Inria Forge under the terms of the LGPL-V2 license.The development of OpenVibe is done in association with the Inria research team BUNRAKU for the national Inria project: ADT LOIC (*cf.* § 7.2).

5.5. CLONES: Closed-Loop Neural Simulations

Participant: Thomas Voegtlin.

The goal of this work is to provide an easy-to-use framework for closed-loop simulations, where interactions between the brain and body of an agent are simulated.

We developed an interface between the Sofa physics engine, (http://www.sofa-framework.org) and the Brian neural simulator (http://www.briansimulator.org). The interface consists in a Sofa plugin and a Python module for Brian. Sofa and Brian use different system processes, and communicate via shared memory. Synchronization between processes is achieved through semaphores.

As a demonstration of this interface, a physical model of undulatory locomotion in the nematode *c. elegans* was implemented, based on the PhD work of Jordan H. Boyle.

5.6. GINNet-DynNet: Decision-making platform

Participant: Marie Tonnelier.

GINNet (Graphical Interface for Neural Networks) is a decision-aid platform written in Java, intended to make neural network teaching, use and evaluation easier, by offering various parametrizations and several data pre-treatments. GINNet is based upon a local library for dynamic neural network developments called DynNet. DynNet (Dynamic Networks) is an object-oriented library, written in Java and containing base elements to build neural networks with dynamic architecture such as Optimal Cell Damage and Growing Neural Gas. Classical models are also already available (multi-layer Perceptron, Kohonen self-organizing maps, ...). Variable selection methods and aggregation methods (bagging, boosting, arcing) are implemented too.

The characteristics of GINNet are the following: Portable (100% Java), accessible (model creation in few clicks), complete platform (data importation and pre-treatments, parametrization of every models, result and performance visualization). The characteristics of DynNet are the following: Portable (100% Java), extensible (generic), independent from GINNet, persistent (results are saved in HML), rich (several models are already implemented), documented.

This platform is composed of several parts:

1. Data manipulation: Selection (variables, patterns), descriptive analysis (stat., PCA..), detection of missing, redundant data.
2. Corpus manipulation: Variable recoding, permutation, splitting (learning, validation, test sets).
3. Supervised networks: Simple and multi-layer perceptron.
4. Competitive networks: Kohonen maps, Neural Gas, Growing Neural Gas.
5. Metalearning: Arcing, bagging, boosting.
6. Results: Error curves, confusion matrix, confidence interval.

DynNet and GINNet are free softwares, registrated to the APP and distributed under CeCILL license, Java 1.4 compatible (http://ginnet.gforge.inria.fr). GINNet is available as an applet. For further information, see http://gforge.inria.fr/projects/ginnet (news, documentations, forums, bug tracking, feature requests, new releases...)

6. New Results

6.1. Spiking neurons

Participants: Hana Belmabrouk, Dominique Martinez, Thierry Viéville, Thomas Voegtlin.

6.1.1. Mathematical modeling

In order to understand the dynamics of spiking neural networks under the influence of a modified synaptic dynamics of single neurons, we study the effect of tonic inhibition on the population activity in spiking neural networks. The aim is to derive mathematical relations of the population activity and some statistics estimated numerically from the simulation of networks [4], [8].

6.1.2. Biophysical modeling

Our understanding of the computations that take place in the human brain is limited by the extreme complexity of the cortex, and by the difficulty of experimentally recording neural activities, for practical and ethical reasons. The Human Genome Project was preceded by the sequencing of smaller but complete genomes. Similarly, it is likely that future breakthroughs in neuroscience will result from the study of smaller but complete nervous systems, such as the insect brain or the rat olfactory bulb. These relatively small nervous systems exhibit general properties that are also present in humans, such as neural synchronization and network oscillations. Our goal is therefore to understand the role of these phenomena by combining biophysical modelling and experimental recordings, before we can apply this knowledge to humans. In the last year, we have studied new aspects of our models of the insect olfactory system [7], [14].

6.1.3. Using event-based metric for event-based neural network weight adjustment

The problem of adjusting the parameters of an event-based network model is addressed here at the programmatic level. Considering temporal processing, the goal is to adjust the network units weights so that the outcoming events correspond to what is desired. The work of [18] proposes, in the deterministic and discrete case, a way to adapt usual alignment metrics in order to derive suitable adjustment rules. At the numerical level, the stability and unbiasness of the method is verified.

The key point, here, is the non-learnability of even-based , since it is proved that this problem is NP-complete, when considering the estimation of both weights in the general case, except for exact simulation. We show that we can "elude" this caveat and propose an alternate efficient estimation mechanism, inspired by alignment metrics used in spike train analysis, thus providing a complement of other estimation approaches, beyond usual convolution metric. At last, the proposed mollification *is* a series of convolution metric, but that converges towards the expected alignment metric.

6.1.4. Predictive learning

In collaboration with Sander Bohte (CWI, Netherlands) and Nicolas Fourcaud-Trocme (CNRS, Lyon), we are developing a model of predictive learning using oscillations in a population of spiking neurons. The model is based on previous work performed in the Cortex group. Our previous model suggested a possible role for neuronal synchronization in unsupervised, predictive-type learning. However, that model was not compatible with sustained oscillations observed in biological networks. We are extending our initial approach in order to allow the network to learn during a stable, steady-state oscillatory regime. This extension involves using type-2 neurons and two distinct types of inhibition.

6.2. Dynamic Neural Fields

Participants: Frédéric Alexandre, Yann Boniface, Laurent Bougrain, Georgios Detorakis, Hervé Frezza-Buet, Bernard Girau, Axel Hutt, Mathieu Lefort, Nicolas Rougier, Wahiba Taouali.

The work reported this year represents both extensions of previous works and new results linked to the notion of neural population, considered at (i) a formal level (theoretical studies of neural fields), (ii) a numerical level (study of functioning and learning rules) and (iii) a more embodied one (implementations of specific functions).

6.2.1. Formal Level

To study the effect of external stimuli on nonlinear neural population dynamics involving constant delays, the work aims to apply the center manifold theorem and derive expressions of the time-dependent centre manifold. It is observed that additive noise and external quasi-periodic driving change the stability of neural populations dependent on the delay [9], [10].

6.2.2. Numerical Level

At the numerical level, specific developments were carried out to assess our software platform, to master functioning rules and to study the performances of new learning rules:

- Adaptation of the BCM rule to multi-modality by adapting the dynamics of the threshold by the use of a feed-back signal generated by a neural field map [1], [26]
- We investigate the formation and maintenance of ordered topographic maps in the primary somatosensory cortex as well as the reorganization of representations after sensory deprivation or cortical lesion. We consider both the critical period (postnatal) where representations are shaped and the post-critical period where representations are maintained and possibly reorganized. We hypothesize that feed-forward thalamocortical connections are an adequate site of plasticity while cortico-cortical connections are believed to drive a competitive mechanism that is critical for learning. We model a small skin patch located on the distal phalangeal surface of a digit as a set of 256 Merkel ending complexes (MEC) that feed a computational model of the primary somatosensory cortex (area 3b). This model is a two-dimensional neural field where spatially localized solutions (a.k.a. bumps) drive cortical plasticity through a Hebbian-like learning rule. Simulations explain the initial formation of ordered representations following repetitive and random stimulations of the skin patch. Skin lesions as well as cortical lesions are also studied and results confirm the possibility to reorganize representations using the same learning rule and depending on the type of the lesion. For severe lesions, the model suggests that cortico-cortical connections may play an important role in complete recovery [6].

6.2.3. Embodied Level

6.2.3.1. Motion detection

We develop bio-inspired neural architectures to extract and segment the direction and speed components of the optical flow from sequences of images. Following this line, we have built additional models to code and distinguish different visual sequences. The structure of these models takes inspiration from the course of visual movement processing in the human brain, such as in area MT (middle temporal) that detects patterns of movement, or area FBA where neurons have been found to be sensitive to single spatio-temporal patterns. This work has been extended to complex movements: to fight, to wave, to clap, using real-world video databases [5].

6.2.3.2. Anticipatory mechanisms in neural fields

We have defined first models of neural fields that include anticipatory mechanisms through the integration of spatiotemporal representations into the lateral interactions of a dynamic neural field. In [20], the case of multiple anticipated trajectories is studied.

6.2.3.3. Action selection

Within the context of enaction and a global approach to perception, we focused on the characteristics of neural computation necessary to understand the relationship between structures in the brain and their functions. We first considered computational problems related to the discretization of differential equations that govern the studied systems and the synchronous and asynchronous evaluation schemes. Then, we investigated a basic functional level : the transformation of spatial sensory representations into temporal motor actions within the visual-motor system. We focused on the visual flow from the retina to the superior colliculus to propose a minimalist model of automatic encoding of saccades to visual targets. This model, based on simple local rules (CNFT and logarithmic projection) in a homogeneous population and using a sequential processing, reproduces and explains several results of biological experiments. It is then considered as a robust and efficient basic model. Finally, we investigated a more general functional level by proposing a computational model of the basal ganglia motor loop. This model integrates sensory, motor and motivational flows to perform a global decision based on local assessments. We implemented an adaptive process for action selection and context encoding through an innovative mechanism that allows to form the basic circuit for other cortico-basal loops. This mechanism allows to create internal representations according to the enactive approach that opposes the computer metaphor of the brain. Both models have interesting dynamics to study from whether a biological point of view or a computational numerical one [2], [12].

6.3. Higher level functions

Participants: Frédéric Alexandre, Laurent Bougrain, Octave Boussaton, Axel Hutt, Maxime Rio, Carolina Saavedra, Christian Weber.

Our activities concerned information analysis and interpretation and the design of numerical distributed and adaptive algorithms in interaction with biology and medical science. To better understand cortical signals, we choose a top-down approach for which data analysis techniques extract properties of underlying neural activity. To this end several unsupervised methods and supervised methods are investigated and integrated to extract features in measured brain signals. More specifically, we worked on Brain Computer Interfaces (BCI).

6.3.1. Using Neuronal States for Transcribing Cortical Activity into Muscular Effort

We studied the relations between the activity of corticomotoneuronal (CM) cells and the forces exerted by fingers. The activity of CM cells, located in the primary motor cortex is recorded in the thumb and index fingers area of a monkey. The activity of the fingers is recorded as they press two levers. The main idea of this work is to establish and use a collection of neuronal states. At any time, the neuronal state is defined by the firing rates of the recorded neurons. We assume that any such neuronal state is related to a typical variation (or absence of variation) in the muscular effort. Our forecasting model uses a linear combination of the firing rates, some synchrony information between spike trains and averaged variations of the positions of the levers [17].

6.3.2. From the decoding of cortical activities to the control of a JACO robotic arm: a whole processing chain

We realized a complete processing chain for decoding intracranial data recorded in the cortex of a monkey and replicates the associated movements on a JACO robotic arm by Kinova. We developed specific modules inside the OpenViBE platform in order to build a Brain-Machine Interface able to read the data, compute the position of the robotic finger and send this position to the robotic arm. More precisely, two client/server protocols have been tested to transfer the finger positions: VRPN and a light protocol based on TCP/IP sockets. According to the requested finger position, the server calls the associated functions of an API by Kinova to move the fingers properly. Finally, we monitor the gap between the requested and actual fingers positions. This chain can be generalized to any movement of the arm or wrist [22].

6.3.3. Wavelet-based Semblance for P300 Single-trial Detection

Electroencephalographic signals are usually contaminated by noise and artifacts making difficult to detect Event-Related Potential (ERP), specially in single trials. Wavelet denoising has been successfully applied to ERP detection, but usually works using channels information independently. This paper presents a new adaptive approach to denoise signals taking into account channels correlation in the wavelet domain. Moreover, we combined phase and amplitude information in the wavelet domain to automatically select a temporal window which increases class separability. Results on a classic Brain-Computer Interface application to spell characters using P300 detection show that our algorithm has a better accuracy with respect to the VisuShrink wavelet technique and XDAWN algorithm among 22 healthy subjects, and a better regularity than XDAWN [21].

6.3.4. Filter for P300 detection

According to recent literature, the most appropriate preprocessing to improve P300 detection is still unknown or at least there is no consensus about it. Research papers refer to different low-pass filters, high-pass filters, baseline, subsampling or feature selection. Using a database with 23 healthy subjects we compared the effect on the letter accuracy (single-trial detection) provided by a linear support vector machine of a high-pass filter with cutoff frequencies from 0.1 to 1 Hz and a low-pass filter with cutoff frequencies from 8 to 60 Hz. According to this study, the best combination is for a band-pass filter of 0.1 to 15 Hz [16].

6.3.5. Processing Stages of Visual Stimuli and Event-Related Potentials

Event-evoked potentials (ERP) in electroencephalograms reflect various visual processing stages according to their latencies and locations. Thus, ERP components such as the N100, N170 and the N200 which appears 100, 170 and 200 ms after the onset of a visual stimulus correspond respectively to a selective attention, the processing of color, shape and rotation (e.g. processing of human faces) and a degree of attention [24].

6.3.6. Exploring the role of the thalamus in visuomotor tasks implicating non-standard ganglion cells

Non-standard ganglion cells in the retina have specific loci of projection in the visuomotor systems and particularly in the thalamus and the superior colliculus. In the thalamus, they feed the konio pathway of the LGN. Exploring the specificities of that pathway, we discovered it could be associated to the matrix system of thalamo-cortical projections, known to allow for diffuse patterns of connectivity and to play a major role in the synchronization of cortical regions by the thalamus.

An early model [23] led to the design of the corresponding information flows in the thalamo-cortical system, that we are now expanding, in the framework of the Keops project § 7.2, to be applied to real visuomotor tasks.

6.3.7. Formalization of input/output retinal transformation regarding non-standard gangion cells behavior

We propose to implement the computational principles raised by the study on the K-cells of the retina using a variational specification of the visual front-end, with an important consequence: In such a framework, the GC are not to be considered individually, but as a network, yielding a mesoscopic view of the retinal process.

Given natural image sequences, fast event-detection properties appears to be exhibited by the mesoscopic collective non-standard behavior of a subclass of the so-called dorsal and ventral konio-cells (K-cells) that correspond to specific retinal output.

We consider this visual event detection mechanism to be based on image segmentation and specific natural statistical recognition, including temporal pattern recognition, yielding fast region categorization. We discuss how such sophisticated functionalities could be implemented in the biological tissues as a unique generic two-layered non-linear filtering mechanism with feedback. We use computer vision methods to propose an effective link between the observed functions and their possible implementation in the retinal network.

The available computational architecture is a two-layers network with non-separable local spatio-temporal convolution as input, and recurrent connections performing non-linear diffusion before prototype based visual event detection.

The numerical robustness of the proposed model has been experimentaly checked on real natural images. Finally, model predictions to be verified at the biological level are discussed [25].

6.4. Embodied and embedded systems

Participants: Yann Boniface, Hervé Frezza-Buet, Bernard Girau, Mathieu Lefort.

6.4.1. InterCell

Our research in the field of dedicated architectures and connectionist parallelism mostly focuses on embedded systems (*cf.* §3.5). Nevertheless we are also involved in a project that considers coarse-grain parallel machines as implementation devices. The core idea of this InterCell project (*cf.* http://intercell.metz.supelec.fr) is to map fine grain computation (cells) to the actual structure of PC clusters. The latter rather fit coarse grain processing, using relatively few packed communication, which a priori contradicts neural computing. Another fundamental feature of the InterCell project is to promote interaction between the parallel process and the external world. Both features, cellular computing and interaction, allow to consider the use of neural architectures on the cluster on-line, for the control of situated systems, as robots.

6.4.2. Hardware implementations of neural models

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, as well as to define hardware-friendly neural models.

- We currently intend to minimize the topological constraints of FPGA-embedded spiking neural fields using reduced neighborhoods but randomly propagating spikes. A preliminary result has been obtained so as to implement massively distributed pseudo-random number generators based on cellular automata that use minimal areas though they produce random streams that pass most randomness tests [19]. These results have also been applied to cellular aurtomata using randomnes in their transition rules [13].
- Researchers have proposed the concept of Central Pattern Generators (CPGs) as a neural mechanism for generating an efficient control strategy for legged robots based on biological locomotion principles. We have developed a reconfigurable hardware implementation of a CPG-based controller which is able to generate several gaits for quadruped and hexapod robots [3].

6.4.3. Towards brain-inspired hardware

Our activities on dedicated architectures have strongly evolved in the last years. We now focus on the definition of brain-inspired hardware-adapted frameworks of neural computation. Our current works aim at defining hardware-compatible protocols to assemble various perception-action modalities that are implemented and associated by different bio-inspired neural maps.

6.4.3.1. Multimodal learning through joint dynamic neural fields

This work relates to the development of a coherent multimodal learning for a system with multiple sensory inputs. We have modified the BCM synaptic rule, a local learning rule, to obtain the self organization of our neuronal inputs maps and we use a CNFT based competition to drive the BCM rule. In practice, we introduce a feedback modulation of the learning rule, representing multimodal constraints of the environment, and we introduce an unler-arning term in the BCM equation to solve the problem of the different temporalities between the raise of the activity within modal maps and the multimodal learning of the organization of the maps [1], [26].

6.4.3.2. Randomly spiking dynamic neural fields

We have defined a new kind of spiking neural field that is able to use only local links while transmitting spikes through the map by succesive random propagations. Such a model is able to be mapped onto FPGAs, while maintaining most properties of neural fields. Early results will be soon published.

7. Partnerships and Cooperations

7.1. Regional initiatives

7.1.1. Action Situated Informatics of the CPER

Participants: Laurent Bougrain, Octave Boussaton, Thierry Viéville.

In the framework of the Contrat de Projet État Région, we are contributing to the axis IS (Informatique Située) through the project CoBras whose goal is to study reinforcement learning to better control a robotic arm in a Brain-Machine interface. We bought a JACO robotic arm for wheelchair by Kinova.

7.2. National initiatives

7.2.1. DGE Ministry grant COMAC "Optimized multitechnique control of aeronautic composite structures"

Participants: Laurent Bougrain, Octave Boussaton, Marie Tonnelier.

The goal of this three-years project is to develop a powerful system of control on site, in production and in exploitation, of aeronautical pieces made of composite. It takes up the challenge of the precise, fast and local inspection on composite pieces of aeronautical structures new or in service by using techniques of non-destructive control more effective and faster to increase the lifespans of the structures of planes. This project requires a decision-making system including fast methods of diagnostic based on several optical technics as non-destructive control.

7.2.2. ANR project KEOPS

Participants: Frédéric Alexandre, Laurent Bougrain, Thierry Viéville.

This «ANR Internal White Project» involving NEUROMATHCOMP and CORTEX Inria EPI in France with the U. of Valparaiso, U. Tecnica Frederico Santa-Maria, and U. De Chili is a 3 years, 248 person-months, sensory biology, mathematical modeling, computational neuroscience and computer vision, project addressing the integration of non-standard behaviors from retinal neural sensors, dynamically rich, sparse and robust observed in natural conditions, into neural coding models and their translation into real, highly non-linear, bio-engineering artificial solutions. An interdisciplinary platform for translation from neuroscience into bio-engineering will seek convergence from experimental and analytical models, with a fine articulation between biologically inspired computation and nervous systems neural signal processing (coding / decoding) [23].

7.2.3. ANR project PHEROTAXIS

Participants: Dominique Martinez, Thomas Voegtlin.

How can animals so successfully locate odour sources? This apparently innocuous question reveals on analysis unexpectedly deep issues concerning our understanding of the physical and biological world and offers interesting prospects for future applications. Pherotaxis focuses on communication by sex pheromones in moths. The main aim of the project is to integrate the abundant experimental data on the pheromone plumes, neural networks and search behaviour available in the literature, as well as that collected or being collected by us at the molecular, cellular, systemic and behavioural levels into a comprehensive global model of the pheromonal olfactory processes. To reach this objective, the consortium combines several groups of specialists with different and complementary fields, in physics (Institut Pasteur IP), neurobiology (INRA) and bio-robotics (Inria).

7.2.4. Project CNRS PEPII: A large-scale, robotically embodied decision making model

Participants: Frédéric Alexandre, Nicolas Rougier, Thierry Viéville.

This project is a collaboration between the “Institut des Maladies neuro-dégénératives” (UMR 5293, team “Approche systémique de la Boucle Extrapyramidale”), Supélec (“Information, Multimodalité, Signal”) and the Cortex team. This project aims at studying the decision making process viewed as a high-level brain function, actioned by a distributed network of cortical and sub-cortical structures, interconnected in positive and negative feedback loops.

7.2.5. Project CNRS PEPII IMAVO

Participants: Nicolas Rougier, Yann Boniface.

This project is a collaboration between the “Institut des Neurosciences Cognitives et Intégratives d’Aquitaine” (UMR 5287), the “Institut des Systèmes Intelligents et de Robotique” (Systèmes Intégrés Mobiles et Autonomes) and the LORIA (Maia and Cortex groups). This project aims at investigating model-free and model-based approaches in the decision process in order to propose a computational model of the decision process in simple tasks.

7.3. European Initiatives

7.3.1. FP7 Projects

7.3.1.1. MathAna

Title: Mathematical Analysis of Anaesthesia

Type: IDEAS

Instrument: ERC Starting Grant (Starting)

Duration: January 2011 - December 2015

Coordinator: Inria (France)

Abstract: General anaesthesia is an important method in today’s hospital practice and especially in surgery. To supervise the depth of anaesthesia during surgery, the anaesthesist applies electroencephalography (EEG) and monitors the brain activity of the subject on the scalp. The applied monitoring machine calculates the change of the power spectrum of the brain signals to indicate the anaesthetic depth. This procedure is based on the finding that the concentration increase of the anaesthetic drug changes the EEG-power spectrum in a significant way. Although this procedure is applied world-wide, the underlying neural mechanism of the spectrum change is still unknown. The project aims to elucidate the underlying neural mechanism by a detailed investigating a mathematical model of neural populations. The investigation is based on analytical calculations in a neural population model of the cortex involving intrinsic neural properties of brain areas and feedback loops to other areas, such as the loop between the cortex and the thalamus. Currently, there are two proposed mechanisms for the charactertisic change of the power spectrum: a highly nonlinear jump in the activation (so-called phase transition) and a linear behaviour.

The project mainly focusses on the nonlinear jump to finally rule it out or support it. A subsequent comparison to previous experimenta results aims to fit the physiological parameters. Since the cortex population is embedded into a network of other cortical areas and the thalamus, the corresponding analytical investigations takes into account external stochastic (from other brain areas) and time-periodic (thalamic) forces. To this end it is necessary to develop several novel nonlinear analysis technique of neural populations to derive the power spectrum close to the phase transition and conditions for physiological parameters.

7.4. International Initiatives

7.4.1. Inria Associate Teams

7.4.1.1. Cortina, associate team with Chile

Participants: Frédéric Alexandre, Thierry Viéville, Laurent Bougrain.

The goal of this associate team is to combine our complementary expertise, from experimental biology and mathematical models (U de Valparaiso and U Federico Santa-Maria) to computational neuroscience (CORTEX and NEUROMATHCOMP), in order to develop common tools for the analysis and formalization of neural coding and related sensory-motor loops. Recording and modeling spike trains from the retina neural network, an accessible part of the brain, is a difficult task that our partnership can address, what constitute an excellent and unique opportunity to work together sharing our experience and to focus in developing computational tools for methodological innovations.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

7.5.1.1. Internships

Elaa TEFTEF (from Dec 2011 until Jun 2012)

Subject: Formalisation de la transformation analogique / événementielle des mécanismes non-standards des cellules ganglionnaires de la rétine.

Institution: Ecole Nationale d'Ingénieurs de Tunis (Tunisia)

TARUN JAIN (from May 2012 until Aug 2012)

Subject: Optimization of reconstruction of brain signals by neural population models

Institution: IIT Delhi (India)

7.5.1.2. Visiting professors/researchers

Peter BEIM GRABEN (from 01/10/2012 until 22/12/2012)

Funding: Inria Mathana

Subject: Detection of metastable states in brain signals

Institution: Humboldt University Berlin, Germany

Chahinez Meriem BENTAOUZA (from 17/11/2012 until 08/12/2012)

Funding: University of Mostaganem

Subject: Etude bibliographique de méthodes d'apprentissage statistique pour l'analyse de signaux médicaux

Institution: University of Mostaganem, Algeria

Samira CHOURAQUI (from 01/04/2012 until 30/04/2012)

Funding: University of Oran

Subject: Modélisation des systèmes non linéaires par des réseaux de neurones

Institution: University of Oran, Algeria

Fatiha HENDEL (from 12/01/2012 until 28/01/2012)

Funding: University of Oran

Subject: Apprentissage et classification automatique

Institution: University of Oran, Algeria

Rodrigo SALAS FUENTES (from 20/04/2012 until 19/07/2012)

Funding: Inria Cortina

Subject: Event-based neural network weight adjustment

Institution: Académico del Departamento de Ingeniería Biomédica, Facultad de Ciencias, Universidad de Valparaíso, Chile

8. Dissemination

8.1. Scientific Animation

8.1.1. Responsabilities

- Principal Investigator of MATHANA (A. Hutt)
- Member of the Board of Directors in Organization of Computation Neuroscience (A. Hutt)
- Member of the steering committee of the french association for Artificial Intelligence (AFIA) (F. Alexandre)
- Member of the board of directors of the LORIA laboratory (B. Girau).
- Head of the Complex systems and AI department of the LORIA laboratory (B. Girau)
- Member of the scientific culture commission (N. Rougier)
- Elected member of the laboratory council (N. Rougier)
- Member of the Comité du Développement Technologique (L. Bougrain)
- Member of the “Bureau du Comité de Projets” (Steering Committee of the Project-Team Committee) (F. Alexandre, until Aug 2012)
- F. Alexandre and T. Viéville are members (and moderators) of the scientific committee of Neuro-Comp, the initiative to gather the french community in Computational Neuroscience (annual conference and web site: http://www.neurocomp.fr/).

8.1.2. Review activities

- Reviewing for journals: Applied Intelligence, RIA, J. Physiol. (F. Alexandre), Physica A, Physical Review E, Physical Review Letters, Neuroimage, Cognitive Neurodynamics, J. Biological Physics, Mathematical Neuroscience, Philosophical Transactions of the Royal Society A (A. Hutt)
- Reviewing for journals: Applied Intelligence, RIA, J. Physiol. (F. Alexandre), Physical Review Letters, Neuroimage, Cognitive Neurodynamics, Mathematical Neuroscience (A. Hutt)
- Member of program committees: Reconfig (B. Girau), CAP (L. Bougrain, F. Alexandre)
- Reviewing (A. Hutt) for the NWO (Science Foundation Netherlands), the ANR and several french regional and territorial agencies (F. Alexandre)

8.1.3. Workshops, conferences and seminars

- Organization of the NeuroComp/KEOpS’12 workshop, Beyond the retina: from computational models to outcomes in bioengineering. Focus on architecture and dynamics sustaining information flows in the visuomotor system. Bordeaux, October the 10th and 11th (F. Alexandre and T. Viéville). http://www.neurocomp.fr/neurocomp-2012
- Co-organization of the “Robots et corps” conference, 18/10/2012, Nancy (N. Rougier)
- Co-organization of CAP’12, French conference on Machine Learning, 23-25/05/2012, Nancy (L. Bougrain)
- Invited speaker and project leader on "Inverse reinforcement learning for a brain-computer interfaces driven robotic arm control", 8th International Summer Workshop on Multimodal Interfaces, eNTERFACE 2012, 02-27/07/2012, Metz (L. Bougrain)
- Invited speaker on “Brain-Machines Interfaces”, "Robots et corps" conference, 18/10/2012, Nancy (L. Bougrain)
- Speaker on "Brain-computer interfaces", meeting on ICT for autonomy during the Autonomic event, 18-19/10/2012, Metz (L. Bougrain)
- Exhibitor on Neuroprosthetics for the Inria Industry meeting on Numerical Simulation for Healthcare and Wellbeing, 21/11/2012, Strasbourg (L. Bougrain)

8.1.4. International cooperations

- in neurophysiology with MPI for Biological Cybernetics (Tubingen)
- in general anaesthesia with University of Auckland (New Zealand)
- on modeling visual attention with university of Chemnitz (Germany)
- in brain-computer interface with the Universidad Autónoma Metropolitana (UAM, Mexico)
- in spike sorting with university of Princeton (USA)

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Many courses are given in universities and schools of engineers at different levels (LMD) by most team members, in computer science, in applied mathematics and in cognitive science. Moreover, several members of the team are implied in various kinds of academic responsibilities: Laurent Bougrain is responsible for the relations of the Master In Computer Science with professional partners, Bernard Girau is head of the RAR speciality of this Master, and member of the Conseil de Collegium Science et Technologie of the University of Lorraine

8.3. Popularization

- The other half-time of Thierry Viéville's activity is dedicated to popularization of science (http://science-info-lycee.fr, http://interstices.info) with about 10 conferences and 20 days of scientific animation.
- Organization of a talk series on Image, Perception, Action & Cognition on a montly basis at the Inria-Nancy Grand Est laboratory (http://ipac.loria.fr/, Y. Boniface, N. Rougier).
- Participation to *Les cafés des sciences et techniques*, "Les Robots, le futur... demain ?" 22/11/2012, Epinal (N. Rougier)
- Participation to *Festival du film du chercheur*, 10/06/2012, Nancy (N. Rougier, L. Bougrain)
- Talk on Neuroprosthetics for the Science's day 2012 at Jules Ferry's school, 11/11/2012, Vandoeuvre-lès-Nancy (L. Bougrain)

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