

BIONICS

European Commission -
US National Science Foundation

Strategic Research Workshop

Bio-inspired Information Technologies

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**Workshop Report and
Recommendations**

BIONICS
Bio-Inspired Information Technologies
- a transatlantic research program

A Proposal made by a Workshop of Scientists

under the auspices of the Future and Emerging Technologies Activity of the
Information Society Technologies Programme of DG XII of the European Commission
and the National Science Foundation of the United States of America

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1 Executive Summary

BIONICS is a common term for bio-inspired information technology, typically including three types of systems, namely:

- bio-morphic (eg neuromorphic) and bio-inspired electronic/optical devices,
- autonomous artificial sensor-processor-activator prostheses and various devices built into the human body, and
- living-artificial interactive symbioses, e.g. brain-controlled devices or robots.

In spite of some restrictive use of the term 'bionics' in popular culture, as well as the unfulfilled promises in the fields of neural networks, artificial intelligence, soft computing and other 'oversold' areas, it was agreed that the name *bionics* as defined above is the right one for the emergent technology also described as bio-inspired information technology (some people are suggesting *info-bionics*). There are numerous programs at several funding agencies which are supporting parts of this field under various other names.

In a collaborative effort among leading researchers from the US and Europe, the workshop “BIONICS – Bio-Inspired Information Technologies”, held in Brussels in June 2001, explored the possibilities of a joint EU-NSF research agenda in the field of bionics. The Workshop is part of a series of strategic research workshops to identify key research challenges and opportunities in Information Technology, under the auspices of the European Commission (programme IST-FET, represented by G. Metakides¹) and the US National Science Foundation (CISE-NSF division, represented by J. Hartmanis).

The Workshop has been divided into four areas: (i) sensing, interfaces and sensors, (ii) human-machine interaction with autonomous sensors and various prostheses (iii) bionic systems and brain controlled automata, and (iv) bionic and bio-inspired device technologies.

The summaries and recommendations of the sessions are included in and represent the main part of this report, which will be presented to US and EU funding agencies. In addition to the presentations and discussions about the content of a later joint call for proposals, several key items of action emerged from the discussions during the Workshop.

The results and recommendations were drafted by some twenty scientists working in both fields of bionics (biologists and IT researchers), as well as a few science policy managers, from both sides of the Atlantic, and it is intended that they serve as a basis for a joint EU-NSF research program. Such a program for discovering and implementing new ideas, methods, and devices in the field of bionics would be beneficial for millions of people suffering from various handicaps and diseases, and could create a new industry in the 21st century. It would largely capitalise on novel opportunities.

There are several driving forces behind bionics, including:

- recent advances in technology

¹ NSF/EC Understanding on Co-operation in Information Technologies - Strategic Research Workshops IST-1999-12077

- advanced microsensor and MEMS technology ('the sensor revolution', including microsensors and actuators)
- low-power computing and communication devices
- new computing paradigms
- advanced neuro-interfacing, biocompatible materials
- new discoveries in neurosciences
 - functional understanding of critical brain functions (e.g. retina, LGN, tactile sensing)
 - better understanding the plasticity of the brain
 - biocompatible interface mechanisms
- social needs and implications related to
 - aging population,
 - security risks at home and public places, as well as
 - in industry and in the environment.

It is recognised that the devices, goods and services related to bionics will soon lead to the emergence of a new multi-billion dollar/euro industry.

To promote early success and leadership in this new industry, a pre-competitive transatlantic collaboration is suggested. Some of the main reasons are:

- while a lot of very active, pioneering, collaborative work is already underway, however, further promotion is required to reach a critical mass
- a multitude of new ideas is emerging and the synergy of the different cultural backgrounds could be highly beneficial
- there is an urgent need for some quasi-standards, and the easiest way is to define them in the research phase
- an organised exchange of doctoral students is needed; students could benefit from a mutually acknowledged credit system, involving a medium-term stay (eg 2-3 semesters) at a host laboratory
- the area is a genuinely multi-disciplinary field where the lack of well-trained and innovative scientists and engineers is a major bottleneck.

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2 Workshop Reports and Recommendations

The program of the Workshop was divided into four Sessions. Each session, with a Chair and Reporter, was introduced by presentations of the scientists assigned to this program. All participants of the Workshop discussed the presentations. Finally, the major goals of the program had been discussed and agreed upon.

2.1 Sensing, Interfaces and Sensors

2.1.1 Major research questions and challenges

Sensory information processing and integration are currently investigated by invasive and non-invasive techniques like multi-electrode recording and neuro-imaging. These studies indicate that brain functions rely on coherent activation of different neurones within a given neuronal structure and even among different brain areas. Analysing or modelling the massive amount of data (images or multi-recording) is a complex task because of the inability of computers to process calculations in parallel like sensory neuronal networks.

Interfaces containing electrodes of different geometries have been developed to record or stimulate cortical neurones or nerve fibres. These interfaces need however to be improved upon, especially regarding their long-term stability and bio-compatibility. For such improvements, *in vitro* systems provide a powerful alternative approach to the use of animals. Cell culture of adult retinal neurones could for instance be used to screen bio-compatible compounds. These *in vitro* models could also be used to design stimulating protocols for the different neuronal populations found in the central nervous systems, ie spiking or graded potential neurones. Finally, such *in vitro* neural networks could also be designed to integrate complex tasks.

Animals display a great variety of sensory systems that easily outperform existing sensors generated by humans. Biosensors designed to follow principles of biological sensory physiology or using biological compounds (eg enzymes, antibodies) have proved commercially successful for glucose testing in diabetic people or for chemical discrimination. For example, an artificial tongue and nose were created, but these elements have neither the exquisite sensitivity of our natural faculties nor the same level of miniaturisation. New polymer structures are currently being developed to increase the chemical sensitivity which can also be obtained from antibodies or enzymes.

2.1.2 Session recommendation

The results of the data analysis could provide a basis for therapeutic decisions such as local surgery, pharmacological treatment or brain prostheses. Prostheses were validated in sensory systems by the development of cochlear implants for auditory deficits. Their extension to include other sensory systems requires the development of an adapted model for sensory system integration in order to generate adequate patterns of stimulation. Therefore, to further understand sensory information processing, normal or pathological brain functions and design sensory prostheses, it is crucial that new tools for real time data analysis and modelling be developed.

As discussed above, interfaces are required to connect biological neural cells to artificial systems to both read and write to nervous systems. In prostheses, for instance, interfaces can transfer adequate stimulation to the biological neural networks. Conversely, interfaces can also collect useful information from the biological neural networks. Experiments *in vivo* have demonstrated the great potential of these interfaces to stimulate motor responses or behavioural decisions. They showed however that specific designs of electrode arrays need to be generated depending on the tissue configuration. They also underlined problems regarding bio-compatibility and long-term stability. Since screening for bio-compatible products may be difficult to achieve *in vivo*, alternative strategies should be developed using *in vitro* neuronal models. As for tissue grafting, the interface should not trigger any rejection reaction or cell degeneration, nor should cell stimulation induce any chemical or physical reactions. In addition, different stimulation protocols must be designed specifically for the different neurone types occurring in the central nervous system, ie, spiking and graded potential neurones. Finally, strategies should be developed to significantly increase long-term contact between neurones and electrodes. Therefore, while interfaces are validated *in vivo*, *in vitro* models should be developed to improve their bio-compatibility and long-term stability.

Recently, some bio-sensors were designed as sensory systems with an array of sensors coupled to an artificial neural network for pattern recognition. The analysis and modelling of sensory systems as described above should therefore allow for a significant increase in the complexity and efficiency of such bio-sensors. Bio-sensors can match and even go beyond the diversity of animal senses. For instance in chemical sense, the principal challenge is to develop new sensors with a wider range of sensitivity, a greater individual selectivity, a better stability and resilience to interference. Such chemical bio-sensors can either rely on biological molecules or artificial structures, provided they are coupled with an adequate transducer. Furthermore, to keep these bio-sensors adapted for industrial or medical applications, miniaturisation of existing and newly developed bio-sensors, their transducers and the corresponding neural network is required. Therefore, the challenges of bio-sensor technology are to significantly increase both their diversity and their miniaturisation.

2.2 Human-Machine Interaction with Autonomous Sensors and Various Prostheses

2.2.1 Scenario and recommendations

Neural prostheses in general and retina implants in particular are becoming a major challenge in the next decade. The architecture of such systems realised by spatial-temporal filter/computer architectures is among the key questions and tasks. Adaptive neural networks can therefore be considered for multidimensional signal processing problems, eg in the case of a learning retina encoder. An interdisciplinary collaboration is important for system development and realisation.

Possible topics are:

- Learning Neural Prostheses
- Learning Bio-Sensors
- Novel Human Sensory Systems.

2.2.2 Major challenges

Some of the major challenges in this field are:

- the development of permanent, two-way interfaces to selected neural circuits, adaptive communications systems and novel distributed system architectures
- the realisation of three-dimensional, smart, stable, long-term brain interfaces
- the optimisation and development of a miniaturised analysis system (the aim of an interdisciplinary research collaboration)
- prevention and forecasting of epileptic seizures, the design and realisation of electrodes and a programmable analogic CNN computer chip implementation, connected in real time to the human brain in epilepsy. This sensing-computing-control system could also be useful in many other applications
- understanding and learning the principles and mechanisms of nature, in many species, for the realisation of new biomedical devices.

2.3 Bionic Systems and Brain-Controlled Automata

2.3.1 Major tasks and challenges

The major tasks and challenges in this field are as follows:

- to understand the structural complexity and the processing mechanisms of the brain

The sheer enormity of constituents and possible states of the brain is emphasised, as well as its ability to adapt with use and in response to novelty with particular emphasis on the somatosensory system. The lack of detailed knowledge about sensorimotor integration, ie, the transfer of information from the sensorial to motor controllers, is highlighted. A major challenge is to uncover and understand the details of the mechanisms by which the cerebellum as a learning machine is capable of making predictions necessary for movement.

- the isomorphism between the structure of the brain and the structure of its output (be it thinking or behavior)

A brain can be described as a composite of dedicated processors, each one of which deals with a problem of some biological importance to the animal it belongs to. An important distinction exists between the simple ones connecting sensorial to motoneurons, also called reflex arcs, and the more complex ones operating on signals internal to the brain which are called association areas. The fact that the job they do usually employs some biological innovation trick (often a structural or functional trick) is emphasised. A key structural and functional direction is described as an aggregate of locally smart, simple processors from which a more complex processor emerges. A list of the methodological approaches necessary to ensure that these and the additional circuits which comprise the brain are fully understood, is as follows:

- 1) Psychophysics, ie, the quantitative treatment of brain output and the formulation of laws that apply to it. An example was provided regarding the position sensitivity of saccades evoked in response to the electrical stimulation of the superior colliculus. Although driven by concerns about the functioning of the superior colliculus, this

research has important implications for the intense debate dealing with the relationship between amplitude versus position control theories. A major challenge for the future will be to extend this work to brain outputs that do not lead to overt behaviour.

- 2) Functional anatomy, necessary to understand structural principles of the brain. An example was provided regarding the spatial extent of activation in the deeper layers of the superior colliculus of a monkey executing saccades of particular metrics. Although driven by concerns about the existence of moving waves coding dynamic movement variables this research has important implications for the representation of the world in neural space. A major challenge for the future will be to extend this work to arbitrary neural maps covering brain areas with complex geometries.
 - 3) Neurophysiology, necessary to understand the signals processed in the brain. An example was provided regarding the discharge pattern of a single cell intracellularly recorded in the alert animal to emphasise the effort that must be invested to understand the neural codes used to represent external physical variables. A major challenge for the future will be to go beyond extracellular recording. It is important to record behaviourally relevant brain signals intracellularly so that we can read excitation and inhibition, and so that there is no ambiguity as to who talks to whom inside the brain.
 - 4) Computational neuroscience, including models from robotics, artificial intelligence, spatial-temporal computing etc, which provides the theoretical framework within which experimental questions are asked, highlights the mechanical, geometric and control issues that the brain must come to grips with, and generates models which help test the adequacy of scientific explanations and engineering applications.
- application areas where the cellular nonlinear/neural network (CNN) paradigm has played and will play a crucial role, including in particular:
 - 1) The use of CNN technology to implement biologically inspired central pattern generators giving rise to forward propulsion. Reaction-diffusion CNNs generating Turing patterns are of key importance, as are their stored programmable hardware/software implementation in analogic topographic microprocessors including microcontrollers, allowing the real-time control of the forward propulsion of some bio-robots. Examples such as walking hexapods and swimming lamprey-like robots are already operational, with their more advanced versions soon to be developed. The possibility of these applications being used in industrial automation and in making household appliances is foreseen.
 - 2) Initial successful experiments using analogic CNN microprocessors for DNA chip evaluation forecast the proliferation of the use of real-time automatic analysis of DNA chips based on the analogue and parallel processing of the information they contain.
 - to understand the mechanisms of a synapse with intrinsic plasticity, and their implementation

Analogic CNN microprocessors might make it in a programmable way. The major challenges: How to make intrinsic, autonomously regulated plasticity? Should any sort of plasticity be implemented in silicon devices? If so, what sort of plasticity do we need?

How to implement the wide ranges of dynamics in signal value and time constants (eg, from 20 ms to hours, days and years)?

- a core problem is the architecture and implementation of spatial-temporal stored programmable microprocessors which can directly handle analogue signal arrays and adapt to changing needs

We also want to include sensory arrays and controlling-acting mechanisms. This new type of sensor-computers is to be endowed with the following features:

- 1) Operation on 2D analog signal flow
- 2) Ability to combine analogue spatial-temporal dynamics and logical operations
- 3) Learning and plasticity
- 4) Wide dynamic range and time-scale range of operation
- 5) The ability to form long-term hybrids with biological systems
- 6) Low power consumption.

The structure and properties of analogic cellular CNN computers seem to be a major candidate in this endeavour, and its further development as well as other directions will also be researched.

Summary of the major research challenges:

- 1) Understanding the processes underlying decision making in brains and machines
- 2) Understanding how the brain represents the world
- 3) Engineering autonomous machines (including their endowment with biologically inspired means of forward propulsion)
- 4) Understanding sensory-motor integration
- 5) Understanding the adaptability and plasticity of brains and machines
- 6) Engineering a new breed of computer architecture which directly processes an array of analogue signals and a signal flow, eg, AnaLogic CNN computers, for use in various applications, including research and decision making.

2.3.2 Session recommendations

1) There is a need to support traditional disciplines such as psychophysics, neuroanatomy, neurophysiology and comparative biology for the study of the various existing biological solutions to a given processing item. The cultivation of such a knowledge base is necessary to provide technology with an archetype to emulate.

2) There is a need to establish interdisciplinary groups of scientists trained in robotics, neuroanatomy, electrical and biomedical engineering, neurophysiology, mathematics, comparative biology, etc. The scientists should be located in such a way as to interact on an everyday basis and the teams should have a critical mass so as to be productive both within and across disciplinary boundaries. Encouraging the collaboration of American and European scientists could contribute in this regard.

2.4 Bionic and Bio-Inspired Device Technologies

2.4.1 Scenario and recommendations

Biological models of the vertebrate, insect and mammalian visual systems have led to bio-inspired algorithms. A device that can implement these algorithms in real time is based on the CNN paradigm. More work is needed to describe the full language of the retina.

Many man-made electro-optical materials and devices have been inspired by biological systems. The motion detection system of the fly is a good example of a useful optoelectronic system for robot piloting and navigation. The rest of the insect world represents a huge data base for future bio-inspired microsensor-processor-actuator units.

The future growth of VLSI faces a number of limitations. Biology has been employed to overcome one problem, namely fault tolerancy, by using loosely coupled, faulty elements. Additional challenges will be sensory fusion, learning systems, and system integration.

Mimicking biology with silicon is very hard. The real niche for bio-inspired systems is at the interface between the digital and analogue world, particularly in the areas of wireless tele-communication and PDAs where power dissipation is critical for implementing powerful signal processing applications like speech recognition.

Current digital trends are toward full integration on a single chip. However, many systems with high dimensional input data need the massive processing of analogue signal arrays. The AnaLogic CNN Computers could handle this problem, as an interesting vehicle for integrating all the various signal processing and decision-making tasks. System-level demonstrations, as well as the inclusion of the complete system on a single chip and the creation of a standard software base and languages are some of the imminent major challenges.

New nano-scale electronic interfaces will offer great improvements in ultra-low-power bionic devices for prosthesis and scientific studies of neural tissue. Future advances in microelectronics and analogue processing will allow dramatic reductions in cost and size. Advanced imaging sensors can benefit greatly from new bio-inspired algorithms.

3 A Vision for Bionics

3.1 Key Research Challenges

It was foreseen that new technologies will have to be developed in order to provide the bionics industry (sometimes also called info-bionics) with reliable tools and techniques for making commercially viable products and services. From this perspective, several key research challenges are to be studied and overcome. The main challenges to be addressed are:

- to understanding the metal-to-bio contact mechanisms for some key interface classes in the deep submicron range, and to develop testbed interfaces ready for standardised clinical trials
- to invent microsensor- and/or actuator-specific yet programmable multidimensional signal-processing platform prototypes, the sensing and actuator parts being integrated into the platform
- to study the inherent dynamic plasticity and interaction between the sensing and computing (signal processing) parts, especially if the signal is topographic (like vision)
- to develop and invent new mixed mode VLSI design techniques for implementing the low power design of analogic topographic microprocessors
- to uncover the neuromorphic functional models in key living sensing-processing-acting (navigating) organs, especially the visual and tactile pathway, and to study crossmodality
- to develop and invent analogic CNN array computing algorithms for dynamic and multidimensional signal processing, fusion, detection and activation functions.

3.2 Implementation of a Transatlantic Research Network

It was agreed that unless we construct, support and organise laboratories or small laboratory networks which will house functional neuroanatomists, psychophysicists, modelers, neurophysiologists, information technologists, VLSI designers, and people familiar with the new analogic cellular (CNN) computing principles and software, working side by side, a real breakthrough will hardly be possible.

- network of task specific testbed laboratories
 - neural/bio-interfaces for generating and sensing neural signals
 - bio-morphic and bio-inspired sensors/activators/communicators
 - prototype analogic sensing/processing/action computers (analogic: a combination of analog spatial-temporal dynamics and logic)
- network for prototype brain controlled and neuromorphic robots
- network for application specific methodologies for prosthetic devices.

The main areas of activity are summarised in the chart. We have selected four core areas of activity and defined eight supporting subject areas.

The proposed program contains a core of enabling technologies and prototype applications in humans, as well as a few components for the carrying out of research in selected mission-critical areas.

Program core with four focus areas:

1) Biological computing and communication models

Bio-morphic functional models are to be developed to understand specific sensing/processing/motor mechanisms. The goal is to find system-level solutions. Out of the many existing models, those candidates are to be selected and/or understood which have a chance to be implemented via some programmable prototype devices.

2) Bio/Neural interface testbeds

For various typical functional settings, interface testbeds are to be developed for testing the living-artificial interfaces. One such testbed interface identified during the Workshop, a neural-electronic interface, is mainly devoted to visual applications. Such prototype testbeds could make possible the comparison and classification of future bionic devices. In this way, different research groups and companies could test their future devices on the same testbed, allowing them to meet emerging international standards. These testbeds would also be used to test bio-compatibility of different materials using different packaging technologies.

3) Programmable AnaLogic spatial-temporal computing and signal processing devices

Practically, all the bionic devices are operating on analogue signals. Many special-purpose electronic signal processing devices, mainly CMOS VLSI chips, have been developed during recent years. There is, however, a pressing need to use a fairly standard, programmable computing device with spatial-temporal interfaces to analogue sensory and/or activating arrays. The AnaLogic Cellular (CNN) Computer architecture, including analogic software, has been identified as one important candidate, and is the result of a genuine transatlantic research collaboration. Communication interfaces and protocols, implemented also by analogue circuits on the chips, have been identified as key aspects to be developed. New efficient methods are required to analyse and process multidimensional signals (including thousands of signals).

4) Prototype prosthetic devices in humans

To test system-level issues, some typical devices built into humans are to be selected and studied in extensive detail. Cochlear implants are an existing candidate, and future retinal implants as well as real-time epilepsy forecasting devices and built-in medication devices are considered as typical case studies. These case studies are to be tested and studied at selected testbed laboratories on both sides of the Atlantic to develop a common reproducible standard in various areas of applications.

As soon as the field of bionics technology has matured and products reach the market, major ethical issues will emerge. These should therefore be studied carefully during the program.

Eight component programs (a nonexhaustive list):

1) Understanding neural processing – learning and plasticity

In this program, specific details of different functionalities as well as of different species will be studied to develop prototype techniques. These results will also serve as components in the system-level models of the first focus area in the core program.

2) Developing bio-morphic sensors/actuators

Various technologies are foreseen, including living/artificial hybrid components. Real-time monitoring and forecasting is also included.

3) Neural-silicon communication systems

Means, methods and implementation details, wired and wireless, signal and power transmission are all included. These results will also serve as components in the system level models of the third focus area in the core program.

4) Analogic hardware/software components

These components are developed for typical computing and signal-processing tasks, and could also serve in the system level of the third focus area in the core program.

5) Developing special neural prostheses

These tasks range from simpler devices up to the most complex prostheses such as retinal implants. These results, once experimentally verified, would serve as components in the fourth focus area of the core program.

6) Bio-inspired and brain-controlled robots

One of the most fascinating areas with promising initial results. Both self contained robots with a high level of fault tolerance and the brain –controlled robots are included.

7) Bio inspired perception systems

Amongst others, various sensor fusion devices, multi-modal surveillance systems and security systems are included.

8) Novel educational efforts

In this emerging discipline, supported also by the sensor revolution as a third wave in electronics industry after the PC and the internet technologies, novel educational efforts are needed on the graduate as well as the undergraduate level. In particular, we are proposing two programs.

One is the support of transatlantic studies for doctoral students working in this field. One particular issue is the establishment of credit transfer for a 1-3 semester-long exchange at a partner laboratory.

The second area is the support of multidisciplinary studies in the undergraduate curriculum. Electronic and computer engineering students are to be “infected” by bio-courses during their earlier semesters, and special courses are needed in the upper division. Likewise, biology students would learn the emerging novel signal processing and computing principles and techniques.

3.3 Proposed Actions

We envision that within a decade, and in a continuously developing fashion, a new industry will emerge serving unprecedented human needs, resulting in

- sensory and other prostheses (visual, auditory, tactile, olfactory, gustatory, motion-based, etc), as well as self-contained medication, forecasting and therapeutic devices built into the human body
- brain-controlled robots and motor prostheses (for both human and industrial use)
- life-like perception/action devices for household, industrial, and medical use (home and community security, telemedicine, home-care, life-like robots/valets, etc.)
- OEM bionic parts to be embedded in many other goods and services.

Most probably, in addition to human needs, the new innovations in micro-sensing and acting devices, MEMS technologies and other related new concepts will accelerate the development of the envisioned products. Our proposed transatlantic research program could serve to accelerate this development in a pre-competitive phase as well as to lead to international standards and maintain the leadership of the participating parties.

We strongly urge the governmental decision makers to act as quickly as possible in implementing this program. As early actions we propose the following:

Implementation of the transatlantic research network

- establishment of a Transatlantic Research Network of task-specific testbed laboratories
 - neural/bio-interfaces
 - bio-morphic and bio-inspired prototype sensors/activators/communicators
 - prototype AnaLogic sensing/processing/action computers
- a Network for prototype brain-controlled, neuromorphic or bio-inspired robots
- a Network for application-specific methodologies for prosthetic devices

4 Appendices

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4.1 Appendix A - The Reports of the four Sessions

Session 1 Sensing, interfaces and sensors

Reporter: Serge Picaud

Subject introduction

Our senses can be very diverse including vision, hearing, touch, taste, and smell. Sensing relies on a sensor array and a neuronal network that process in parallel the spatio-temporal sensory information to provide an immediate and often vital motor decision. This resulting behavioural decision may not always rely on information from a single sense but it can integrate different sensory inputs. On one hand, multi-electrodes can record these sensory information processing as patterns of neuronal activities, on the other hand, such electrodes, interfaces between neurones and artificial machines, can also be used to stimulate biological neural networks with artificially processed sensory information. To generate such artificial sensory systems, biosensors can be designed by either mimicking natural sensors, using biological molecules or taking advantages of sensory system architectures. Beyond the scientific interest, these artificial biosensors, their integration algorithms and interfacing them with biological systems could have potential applications in robot sensing, intelligent detectors, medical diagnostic, or human sensory prostheses.

Interfacing multi-electrode arrays with cortical structures and nerve fibres.

Dick Norman

Topic

Multi-electrode arrays were designed with different geometries to record cortical activity or stimulate nerve fibres. These arrays were validated in vivo showing their great potential for mapping cortical representations or triggering muscle contraction. Finally, this in vivo validation of the arrays has allowed to define needed improvements for such interfaces.

Summary

The cortex was recorded with square arrays of 100 multi-electrodes 1mm high at a 0.4mm spacing. These arrays allowed to generate maps of cortical activity, 1/3 of the electrodes providing field potential, 1/3 multi recording units and 1/3 single recording units. The stability of this recording was not demonstrated with an array but with one electrode, over a 3-year period. Data analysis of cell firing rate enabled to predict hand movement in a spot positioning behavioural task. Multi-electrode arrays with a different geometry were generated to stimulate nerve fibres. In order to reach fibres located at different eccentricities in the nerve, electrodes were produced with increasing sizes along the nerve fibre axis. Implementing these arrays on sciatic nerves showed that each electrode triggered cell contraction in specific areas of the muscle and that all areas were covered by some of the electrodes.

Research issues and challenges

Spatio-temporal representation of brain activity should be generated from multi-electrode recording to understand brain information processing. Such brain maps could then also be used to generate electrical stimulation, the psychophysics of which needs to be investigated. The developments of microelectrode arrays should focus on 1) increasing electrode density, 2) improving the compliance of the array with soft brain tissues, 3) increasing the electrode stability, 4) enhancing the array biocompatibility, 5) designing new array geometries depending on given structures. Finally, human experimentations will be needed to evaluate the benefit of neuronal electrical stimulation in different pathologies.

Retina: information processing and interfaces

Serge Picaud

Topic

Therapeutic strategies such as photoreceptor transplantation or pharmacology were recently elaborated to slow down photoreceptor degeneration. The different in vivo and in vitro animal preparations that are developed for such studies could provide adequate models to assess biological interfaces.

Summary

1) Concerning retinal implants, our objectives focus on their functional evaluation on in vivo and in vitro models with electrophysiological techniques. In fact, the retina appears as an adequate model to develop interfaces with neuronal tissue since adult retinal neurones can survive in culture for months. First, such a culture could be used to test new products entering in the composition of implants; these products should for instance limit glial proliferation that could progressively hinder electrical contact with the neurones. Second, adult retinal cell cultures could be taken to advantage to define specific protocols to stimulate for long periods either graded potential or spike generating neurones.

2) Human adult retinal neurones also survive in culture for months when prepared from post-mortem retina. Since we showed further that they maintain normal physiological features in vitro, this in vitro model should become very valuable to define retinal information processing in the human retina and therefore design adequate stimuli for retinal implants. These data on retinal information processing should also become very useful for system of pattern recognition. In fact, genetically modified mice may soon provide most of the data on retinal function, a consideration that led us to participate to a mouse mutant screening. Digital models of mouse retina may inversely help to predict expected phenotypes of mutant mice and thus direct the production of transgenic animals.

Research issues and challenges

Several challenges may face the field of vision in the years to come, the major goals being 1) to build retinal implants that could provide useful visual information to blind people, 2) to use visual information processing to generate new systems for pattern recognition. Furthermore,

the retina may also provide adequate in vitro and in vivo models to develop interfaces between natural systems and stimulators from in vitro to in vivo conditions.

Artificial sensing machines for odorants, taste and chemicals.

Conrad Bessant

Topic

Chemical sensing (olfactory or taste) is an area where humans and animals invariably outperform machines. Analysers are indeed less sensitive and less reliable than biological sensory systems. Furthermore, they cannot dissect as complex mixtures and recognize so many flavours. Even if more efficient solutions are required, these artificial sensors have a very important role for very frequent analyses such as screening disease or identifying pollutants

Summary

In recent years there have been moves to design sensor systems based on, or even including components from, sensing systems found in nature. A prime example is biosensors – the use of biological sensor recognition elements in an artificial system (e.g. use of an enzyme or antibody coupled to an electrochemical transducer). Other methods mimic biological systems, either by artificial fabrication of recognition elements (e.g. molecularly imprinted polymers) or by using a mechanical analog of a biological system. The “electronic nose” is an important example of the latter. This uses an array of sensors, much like the array of cells in the mammalian nose, coupled to pattern recognition software that is typically based on a computer simulation of the neural network processes occurring in the brain. These life-like chemical detection systems have proved commercially successful in specific niche areas, such as blood glucose monitoring and wine authenticity testing, but there remain a number of obstacles to their widespread use.

Research issues and challenges

The principal challenges are miniaturisation, accuracy, sensor stability, and resilience to interferences. Possible approaches to these challenges include miniaturisation of laboratory systems, and integrated development of sensor hardware and data analysis algorithms.

Neural dynamics in cognition

Andreas Engel

Topic

Neurobiological and neurocomputational research of the past two decades has provided very convincing evidence that studying the temporal dynamics of neural systems may be one of the keys to understanding the biological basis of cognition. Future challenges in the field of neural

dynamics are discussed with respect to possible goals, useful experimental strategies and required technical developments.

Summary

Key objectives for future project on neural dynamics are (i) the investigation of neural dynamics in more realistic behavioural contexts, in order to approach the basic aspects of real-world cognition; (ii) a conceptual paradigm shift away from the classical representationist framework toward action-/behaviour-oriented approaches; (iii) a consequent deconstruction of the serial-hierarchical picture of the brain by emphasizing the role of top-down mechanisms, cross-system interactions, and intermodal binding.

Achieving these objectives will require the design of new experimental strategies that very likely have to include (i) the usage of more realistic stimulus setups and complex sensorimotor paradigms; (ii) experimentation on unrestrained subjects/animals with endogenously controlled and self-paced behaviour; (iii) reinforcing complementarities of human and animal studies; (iv) complementing neurocomputational models by building artifacts for real-world and real-time testing of hypotheses.

Research issues and challenges

Implementation of these strategies will, in turn, rest on successful development of new research technologies that allow (i) the monitoring of complex behaviours in realistic environments; (ii) the massively parallel recording of neural signals at the cellular level; (iii) the observation of neuronal dynamics in complex action contexts over extended periods of time, and (iv) the analysis of high-dimensional data sets.

In vitro biological neural network controlling artificial systems

Massimo Grattarola

Topic

The direction of the research activity of my Group (WWW.bio.dibe.unige.it) in the near future can be summarized by a statement as follows :To be able to train in vitro networks of neurons to control artificial bodies towards the accomplishment of specific tasks. In a broad sense this research should extend the research areas of brain – computer interfaces, in which nervous signals are used to control external devices and that of neuro-prostheses, in which artificial devices directly stimulate the nervous system.

Summary

The extension consists in the fact that, while in the above mentioned approach artificial devices are intended as substitutes of missing or damaged brain functionalities, our research intends to use in vitro networks of real neurons as information processing tools. This research has been partially stimulated by the pioneering study very recently started in USA (Chicago's

Northwestern University) and consisting in the control of a roving robot by the brain of a simple organism (i.e. a lamprey, http://www.newscientist.com/news/news_224233.html).

Research issues and challenges

One of the main challenges of this research is the development of interfaces and of stimulation protocols (both electrical and neuropharmacological) appropriate to create, thanks to the enormous plasticity properties of the networks, subnetworks of input neurons and of output neurons. The achievement of this result will represent a fundamental step forward both in the understanding of brain functions as well as in the inspiration of new neurobiology-driven formal neural network and neuromorphic devices.

There are two possible long-term breakthroughs to be expected: a) Computers which learn from their own experience. B) Brain control of artificial bodies.

Further research will be certainly needed: to design an optimal microenvironment for the networks so to use them for a long period (months, a big improvement over the lamprey short term experiment); to generate input and output neurons. Neurons with high synaptic plasticity will be needed, such as neurons from the brain of mammalian embryos.

Neuro-imaging and brain circuit integration

Marc Van Hulle (Patrick De Meziere)

Topic

One of the most promising neuro-imaging techniques, for both diagnostic as well as basic brain research purposes, is functional magnetic resonance imaging (fMRI), since it is non-invasive, and since the recorded signal is a more direct measure of metabolic activity.

Summary

Current statistical tools for analysing fMRI data are aimed at investigating the relationship between the experimental paradigm and local changes in brain activity. They assume that the voxels in the discretized brain image are independently and identically distributed and, thus, that they obey univariate statistics. However, since cognitive functions result from interactions between brain regions, the independence assumption is likely to be invalid. The challenge for the future is to develop new concepts and tools that consider the active brain regions as part of a network, possibly with recurrent and task- or condition-dependent connections. Due to the extremely low signal-to-noise-ratio of the recorded fMRI signals and to the occurrence of artefacts (e.g. cardio-respiratory artefacts with non-stationary and non-Gaussian behaviour), additional research in signal processing, computer vision, statistics, and network modelling is needed in priority. Furthermore, one should be able to constrain the network model by the known anatomy of the connections, or by the expected connectivity for a given neurological disease, or by some other prior.

Research issues and challenges

The main challenge of neuro-imaging is to design dynamic network models taking into account known anatomical brain connectivity. Improving signal processing should further increase signal to noise ratio by removing artefacts. The issue is not only understanding brain functions but to design a powerful diagnostic approach for brain disorders.

Session major research questions:

Sensory information processing and integration are currently investigated by invasive and non-invasive techniques like multi-electrode recording or neuro-imaging. These studies indicate that brain functions rely on coherent activation of different neurones within a given neuronal structure and even among different brain areas. Analysing or modelling the data (images or multi-recording) is a complex task because computers cannot process calculations in parallel like sensory neuronal networks.

Interfaces containing electrodes of different geometries were generated to record or stimulate cortical neurones or nerve fibres. These interfaces need however to be improved especially regarding their long-term stability and biocompatibility. For such improvements, in vitro systems provide a powerful alternative approach to the use of animals. Cell culture of adult retinal neurones could for instance be used to screen biocompatible compounds. These in vitro models could also be used to design stimulating protocols for the different neuronal populations found in the central nervous systems: spiking or graded potential neurones. Finally, such in vitro neural networks could also be designed to integrate complex tasks.

Animals display a great variety of sensory systems that easily outperform existing sensors generated by humans. Biosensors designed after sensory system or using biological compound (enzyme, antibodies) have proved commercially successful for glucose test in diabetic people or for chemical discrimination. An artificial tongue and nose were for instance created but these elements do not have the complex sensitivity of our senses nor do they have the same level of miniaturisation. New polymer structures are currently developed to enlarge the chemical sensitivity which can also be obtained from antibodies or enzymes.

Session recommendation

Sensory input integration and more generally brain functions are currently investigated with invasive (multi-electrode recording) and non-invasive (neuro-imaging) techniques that require massive data analysis. Furthermore, modelling these data is very difficult since computers cannot process parallel information operated by sensory systems. Analysing and modelling these data is however very important to understand brain functions in both normal conditions and in different brain-associated diseases. In the later context, the result of the data analysis could provide basis for a therapeutic decision such as local surgery, pharmacological treatment or brain prostheses. Prostheses were validated in sensory systems by the development of cochlear implants for auditory deficits. Their development for other sensory systems requires the development of adapted model for sensory system integration in order to generate adequate pattern of stimulations. Therefore, to further understand sensory information processing, normal or pathologic brain functions and design sensory prostheses, it appears crucial to develop new tools for real time data analysis and modelling.

As discussed above, interfaces are required to connect biological neural cells to artificial systems. In prostheses, for instance, interfaces can transfer the adequate stimulations to the biological neural networks. Conversely, interfaces can also collect useful information from the biological neural networks. Experiments *in vivo* have demonstrated the great potential of these interfaces to stimulate motor responses or behavioural decisions. They showed however that specific designs of electrode arrays need to be generated depending on the tissue configuration. They also underlined problems regarding biocompatibility and long-term stability. Since screening for biocompatible products may be difficult in *in vivo* conditions, alternative strategies should be developed using *in vitro* neuronal models. As for tissue grafting, the interface should not trigger any rejection reaction or cell degeneration. Furthermore, cell stimulation should not induce any chemical or physical reactions. In addition, different stimulation protocols have to be designed specifically for the different types of neurones occurring in the central nervous system, spiking and graded potential neurones. Finally, strategies should be developed to increase long-term contact between neurones and electrodes. Therefore, while interfaces are validated *in vivo*, *in vitro* models should be developed to improve their biocompatibility and long-term stability.

Recently, some biosensors were designed as sensory systems with an array of sensors coupled to an artificial neural network for pattern recognition. Analysing and modelling sensory systems as described above should therefore allow to increase the complexity and efficiency of such biosensors. Biosensors can cover and even go beyond the diversity of animal senses. For instance in chemical sense, the principal challenge is to develop new sensors with a wider range of sensitivity, a greater individual selectivity, a better stability and resilience to interferences. Such chemical biosensors can either rely on biological molecules or artificial structures provided they are related to an adequate transducer. Furthermore, to keep these biosensors adapted for industrial or medical applications, miniaturisation of existing and newly developed biosensors, their transducers and the corresponding neural network is required. Therefore, the challenges of biosensors rely in increasing their diversity and their miniaturisation.

Session 2 Human-machine interaction with autonomous sensors and various prostheses

Reporter Ronald Tetzlaff

Introduction (R. Eckmiller)

Neural prostheses and Retina implants have been introduced. The architecture of such systems realized by spatio-temporal filter structures have been discussed in detail. Thereby, adaptive neural networks can be considered for signal processing problems, e. g. in the case of a learning retina encoder. A interdisciplinary collaboration is important for the system development and realization.

Possible topics are:

Learning Neural Prostheses

Learning Bio Sensors

Novel Human Sensory Systems

Advances in Neural Implants

D. Kipke

In this presentation the cortical control of prostheses has been discussed in detail. It has been shown that in general these systems consist of a control system and a neural interface. As an old example the cortical control of a robot arm in an animal experiment with an monkey has been presented. The control applications are limited by interfaces, e. g. electrodes lose the contact after a certain time. The properties of the third generation of implants are e. g. high channel count (500 - 1000), bioactive coatings and flexible engineering surfaces. Furthermore, hybrid implants for the micro-drug delivery have been discussed. Challenges are permanent, two-way interfaces to selected neural circuits, adaptive communications systems and novel distributed system architectures.

New Directions in Multichannel Neural Interfaces

P. Rousche

The target area is the development of 3-dim interfaces with multichannel input and output which could be integrated into existing neural networks to provide a increased quality of life of handicapped persons. The goal is to realize bioactive devices to communicate with single neurons and the implementation of control systems with multichannel multi-area neural interfaces for the activation and monitoring of neural circuits. A single electrode intracortical microstimulation in auditory cortex of a behaving rat has been presented. The challenge is the realization of 3-dim smart, stable long term brain interfaces.

Nonlinear Analysis of Brain Electrical Activity in Epilepsy

K. Lehnertz

A detailed discussion of Epilepsy which is a disorder of the brain has been given. An analysis of brain electrical activity will be performed for each patient in a presurgical evaluation. Thereby in many cases it is necessary to consider invasive recordings for diagnostical purposes. With a nonlinear analysis of brain electrical activity precursors of an impending seizure can be observed several minutes before the onset of an epileptic seizure in many cases. The optimization and development of a miniaturized analysis system is the aim of an interdisciplinary research collaboration.

Anticipation of Epileptic Seizures by Cellular Neural Networks

R. Tetzlaff

The realization of a programmable miniaturized system for an online detection of precursors of an impending seizure and for the prevention of the seizure generation is the goal of the interdisciplinary research project, which has been discussed in this presentation. By using Cellular Neural Networks (CNN) different feature extraction methods have been proposed. These features show distinct changes several minutes only before the onset of an epileptic seizure in all considered cases allowing possibly for the first time the realization of a CNN based mobile system for the anticipation of seizures.

Challenges in the epilepsy project are the design and the realization of electrodes and a programmable CNN realization used as a control system of the human brain in epilepsy. Especially, the control system can be also considered for any other application.

Living Tissue Mechanisms and Concepts as Models for Biomedical Microsystems and Devices

A. Dittmar

Various examples of living tissue mechanisms and concepts has been given in this presentation as a inspiration for the design of new sensors and actuators. A comparison of the mechanisms of different man made devices to those of living tissues show that e. g. the parallelism of artificial devices is usually poor. Principles in nature are important sources for the determination of new methods. A self repairing watch has been presented as an example. The main statement of this contribution is to understand and to learn the principles and mechanisms of nature for the realization of new biomedical devices.

Bionics: Contribution from two European task forces

G. Dorffner

A report about the results of two task forces in Bionics in the framework of the FET programme has been given in this presentation. Firstly, the stock-taking and survey activity of a group of experts on “Lifelike Perception Systems” has been considered. Secondly, the major research directions in Bionics have also been discussed in a session on the “Bio-IT Interface” of a FET strategic workshop. Thereby, the themes “Bio-inspired processing architectures and paradigms” and “Evolvable lifelike artefacts” were seen central in the Bio-IT Interface panel in this workshop.

For the bio inspired design and realization of artificial devices new knowledge of principles in nature should be considered. The conclusion of this presentation is that interdisciplinary research is an important basis in biotechnology.

Challenges of this session are underlined in the text.

Session 3 *Bionic systems and brain controlled automata*

Reporter Adonis Moschovakis

J. Hámori briefly introduced issues related to the structural complexity and the processing power of the brain. The sheer enormity of constituents and possible states of the brain was emphasized as was its ability to adapt with use and in response to novelty with particular emphasis to the somatosensory system. The lack of detailed knowledge about sensorimotor integration, i.e., the transfer of information from the sensoria to motor controllers was highlighted. A brief overview of the motor system was provided with particular emphasis on the interplay between the parietal cortex (responsible for the representation of movement geometry) the prefrontal cortex (responsible for making decisions about movements) the basal ganglia (responsible for selecting the appropriate program) and of the cerebellum (responsible for the calibration and refinement of movements).

A brief outline of the quantitative anatomy of the cerebellum was presented next. The quasi-crystalline structure of the cerebellar cortex, the cell classes it contains, their synaptic interconnections (with particular emphasis on the glomerulus), the synaptic influence they exert on each other and their plastic modification were summarized. The possibility that the cerebellum is a learning machine making predictions necessary for movement and the debate between the Marr-Ito-Albus cerebellar hypothesis of learning versus the Llinas hypothesis of brain stem learning was highlighted.

A. Moschovakis emphasized the isomorphism between the structure of the brain and the structure of its output (be it thinking or behavior). The brain was described as a composite of processors each one of which deals with a problem of some biological importance to the animal it belongs to. The distinction was made between the simple ones connecting sensoria to motoneurons, also called reflex arcs, and the more complex ones operating on signals internal to the brain which are called central pattern generators. The fact that the job they do usually employs some biological trick (often a structural trick) was emphasized. It was further described as an aggregate of locally smart, simple processors which together make a more complex processor. The example was offered of the complex hierarchical organization of

motor systems. It was pointed out that the saccadic system is made of the neural integrator (a circuit integrating eye velocity to produce a signal proportional to eye position and thus ensure eye stability), the burst generator (a circuit which matches the frequency content of command signals to the impedance of the effector) and the metric computer (a circuit which ensures that motor commands are coded in the frame of reference of the visual stimulus) and which is more globally smart (in the sense that it manages to move the eyes fast enough so that vision is not compromised). It was then pointed out that the saccadic system, together with the smooth pursuit system, the vestibuloocular reflex, the optokinetic system and the vergence/divergence system make the oculomotor system, which is even more globally smart, that this together with the head controller make the gaze control system, etc. It was pointed out that humanity has made considerable progress along a broad front in its effort to understand how these circuits work. A list was provided of the methodological approaches necessary to ensure that these and the additional circuits which comprise the brain are fully understood:

1) Psychophysics, i.e, the quantitative treatment of brain output and the formulation of laws that apply to it. An example was provided regarding the position sensitivity of saccades evoked in response to the electrical stimulation of the superior colliculus. Although driven by concerns about the functioning of the superior colliculus this research has important implications for the debate raging between amplitude versus position control theories. A major challenge for the future will be to extend this work to brain output that does not lead to overt behavior.

2) Anatomy, necessary to understand structural principles of the brain. An example was provided regarding the spatial extent of activation in the deeper layers of the superior colliculus of a monkey executing saccades of particular metrics. Although driven by concerns about the existence of moving waves coding dynamic movement variables this research has important implications for the representation of the world in neural space. A major challenge for the future will be to extend this work to arbitrary neural maps covering brain areas with complex geometries.

3) Neurophysiology, necessary to understand the signals processed in the brain. An example was provided regarding the discharge pattern of a single cells intracellularly recorded in the alert animal to emphasize the effort that must be invested to understand the neural codes used to represent external physical variables. A major challenge for the future will be to go beyond extracellular recording. It is important to record behaviorally relevant brain signals intracellularly so that there is no ambiguity as to who talks to whom inside the brain.

4) Computational Neuroscience, Robotics and Artificial Intelligence, which provide the theoretical framework within which experimental questions are asked, highlight the mechanical, geometric and control issues that the brain must come to grips with, generate models which help test the adequacy of scientific explanations and engineer applications.

L. Fortuna presented two particularly interesting applications based on cellular neural networks (CNNs) endowed with a threshold-saturation non-linearity:

1) Use of CNNs to implement biologically inspired central pattern generators giving rise to forward propulsion. Reaction-Diffusion CNNs generating Turing patterns were briefly described as was a programmable hardware CNN structure allowing the real time control of the forward propulsion of some bio-robots. Examples were provided of walking hexapods and swimming lamprey-like robots. The possibility was suggested to use these applications in industrial automation, such as on-line routing of objects moved on conveyor belts.

2) A new CNN based technique was described allowing for the automatic analysis of DNA-chips based on the analogue and parallel processing of the information they contain.

V. Gál provided a comparative overview of plasticity in synapses and in CNNs. The limitations and prospects of obtaining plasticity in silico were presented. It was explained that current silicon implementations of synapses are of very low complexity due to technical difficulties.

Presently, silicon neurons have few synapses of programmable strength and has no intrinsic, autonomously regulated plasticity. The implementation of such a "smart" feature requires intensive, costly efforts. Two questions were posed:

- 1) Should any sort of plasticity be implemented in silicon devices?
- 2) If so, what sort of plasticity should one need?

In the speaker's opinion, the biological solutions to analogous problems should be emulated, if for no other reason than the fact that there is a need for silicon devices to process information about the real world in real time. It was pointed out that the biggest technological challenge in this field is to mimic the flexibility that synapses display in terms of time (20 ms - hours, days and years) whereas presently available silicon neurons have much shorter time constants (1 ns - 10 ms).

T. Roska pointed out that a plethora of inexpensive sensors are appearing in the market. He went on to present a list of properties that new computers should be endowed with, namely:

- 1) Operation on 2-D analog signal flow.
- 2) Ability to combine analog spatio-temporal dynamics and logical operations (AnaLogic).
- 3) Learning and plasticity.
- 4) Wide dynamic range and long time-scale operation.
- 5) The ability to form long-term hybrids with biological systems.
- 6) Low power consumption.

The structure and properties of the AnaLogic Cellular (CNN) Computers, as topographic (e.g. Visual) Microprocessors with tested TeraOPS speed chips was presented and the extent to which they are endowed with the requisite properties was examined. A case study for real time 3-D reconstruction of the image of the heart from echocardiographic images was presented.

Major research challenges:

- 1) Understanding decision making in brains and machines.
- 2) Understanding how the brain represents the world.
- 3) Engineering autonomous machines (including their endowment with biologically inspired means of forward propulsion).
- 4) Understanding sensory-motor integration.
- 5) Understanding the adaptability and plasticity of brains and machines.

6) Engineering AnaLogic Cellular (CNN) Microprocessors for use in bio-inspired sensing-processing-action devices and real time 3-D imaging, real time spike classification, decision making, etc.

Session recommendations:

1) There is a need to support traditional disciplines such as psychophysics, neuroanatomy, neurophysiology and comparative biology to study biological solutions to computational problems. Unless such a knowledge base is cultivated, technology won't have much of an archetype to emulate.

2) There is a need to establish interdisciplinary groups of scientists trained in robotics, neuroanatomy, electrical and biomedical engineering, neurophysiology, mathematics, comparative biology, etc. The scientists should be located in such a way as to interact on an everyday basis and the teams should have a critical mass such as to be productive both within and across disciplinary boundaries. Encouraging the collaboration of American and European scientists could contribute in this regard.

Session 4 Bionic and bio-inspired device technologies

Reporter Dean Scribner

Frank Werblin

Recent studies at Berkeley have shown that there exist about 12 distinct and simultaneous image representations in the retina which likely form dynamic channels into the higher visual centers of the brain. A major area of future research will be to determine how this information is processed as well as determining the associated natural language that is used by the retina to communicate this information to the LGN and visual cortex. From existing knowledge of the retina and future advances, better biological models of the retina will be constructed which in turn will lead to bioinspired algorithms for use in machine vision and other areas of image processing.

A device that can implement these algorithms in realtime is CNN- a supercomputer on a chip that has an architecture very similar to the retina. Berkeley uses the chip in two complimentary ways. First, as an algorithm check they program their computer to behave like a retinal network, then measure the network properties to check "hypothesis". Second, as an hypothesis generator one can "imagine" that a specific set of interactions exists in the retina and create algorithms for the chip that behave like this network, then look to the retina for similar behavior. The resulting algorithms represent retinal behavior that can be used for practical purposes such as the "camera" for the front-end of a prosthetic vision device. One area that requires more work is the development of the full language of the retina.

Nicolas Francescini

Many hi-tech electro-optical materials and devices have been inspired by biological systems. Some examples are: the compound (facet) eye of nocturnal moths and the graded index lenses, optical fibers, and anti-reflective coatings that were derived from it; the crayfish compound eye and grazing incidence X-ray lenses, X-ray telescopes, and solar concentrators; the Limulus compound eye and lateral inhibition; the fly compound eye, the fly gyrometer and their smart processors... Overall there is a tremendous amount of knowledge that can be read in

biological sensors in terms of integrated optics, neuronics, and micro-mechatronics. Insects' refined sensors were shown to be at the service of dedicated neural processors which guide the animal in behavioral acts that can be analyzed quantitatively: navigation, food collection, mate chasing, homing... In many ways these highly developed animals exhibit superior abilities to sense and act, while being able to fuse information from many sensory modalities, and to learn rapidly. The neural circuits of these animals rests on uniquely identifiable neurons, and can therefore often be analyzed more easily than in the vertebrates.

The process of motion detection system in the fly's eye is a good example of a neural circuit that was used for robot automatic piloting. Since 1980, work at CNRS in Marseille has focused on analyzing fly motion detecting neurons with microelectrodes under single cell illumination of the retinal mosaic. One outcome of this research was the development of (electronic) motion detectors copied from the fly. A further outcome was the design and construction of various mobile robots, including aerial ones, whose eye makes use of the fly motion detectors to see their environment, avoid obstacles, or track objects at high speed. A recent discovery of the laboratory has been the micro-scanning of the fly retina, as recorded by microelectrodes in the flying animal. A twin-engine, twin propeller micro-robot using this system in connection with a motion detector was shown to be able to fixate an edge or a bar visually, and track it to an accuracy much better than expected from the static resolution of the eye. One goal is to develop fully functional flying robots using biologically inspired circuits and systems, and to learn more, in return, about basic problems in sensory-motor processing. Note that the fly has only 10^6 neurons (a very small neural system compared to humans), but has tremendously high performances in terms of piloting and sensory-motor coordination.

The insect world represents a huge and original data base for future bio-inspired systems, vehicles, and micro-vehicles

Giacomo Indiveri

The Institute of Neuroinformatics in Zurich develops vision chips, head-eye systems, and roving robots based on principles of the biological nervous system. There are a number of challenges that need to be overcome in the near future, e.g. sensory fusion, learning systems, and system integration. Similarly, there are a number of approaches that need to be studied: e.g. neuromorphic systems (and related infrastructure); multi-chip systems and related integration with motors and actuators; and neuromorphic software/algorithms/hardware for applications such as navigation, pilotage, and foraging. Specific examples of chips currently being developed are silicon retinas, velocity/detection/tracking systems, and selective attention chips.

The predicted near term limitations to VLSI's future growth is another driving force for much of the new interest in neuromorphic technologies. Digital systems have become the mainstay of modern microelectronic engineering, however, such system are not very fault-tolerant and require precisely fabricated elements - biology has learned how to successfully self-organize huge networks using loosely coupled, faulty elements. Also, digital takes $\sim 10^{-8}$ J/operation which is 10^4 times more than analog and requires much less real estate. Ultimate success with neuromorphic technologies will require multidisciplinary teams that combine various methods from the fields of control theory, information theory, and traditional neuroscience.

Angel Rodriquez-Vazquez

Bioinspired visual microprocessors are being developed in Seville – the emphasis is on parallel image processors using CNN-UM chips. There may be a number of interesting

applications of CNN-like devices in consumer electronics (TV, radios, telephones, etc.) where an interface between analog and digital is required. Similarly, the CNN technology could also be used in a manner similar to mixed-mode analog-digital devices, e.g., camera-on-a-chip or multidimensional sensors/actuators. A variation on this theme is to develop mixed-mode circuits that for imaging CNN applications. This could include a broad range of imaging operations using CNN and related architectures for CMOS focal plane micro-processors.

A device that has been fabricated and tested at the Seville facility is the ACE4K chip that has 64 x 64 cells (172 transistors per cell on a chip 9.1 mm x 9.5 mm). The next chip is the ACE16K which will use 0.35 micron design rules and has 128 x 128 cells on an 11.9 mm x 12.2 mm chip. This device is scheduled to go out from the foundry in July 2001.

The challenge in the short term is interfacing analog sensors with digital computers and networks.

Chris Toumazou

Mimicking biology with silicon is very hard. The real niche for bio-inspired systems is at the interface between the digital and analog world, particularly in the areas of wireless telecommunication and PDA's where power dissipation is critical for implementing powerful signal processing applications like speech recognition. A simplistic description of the future application areas is that it is like an egg, wherein the vast power of digital electronics is the inside of the egg and the advanced analog processing is the shell of the egg. Digital processors have been very successful at performing high speed precise processing, but they are power-hungry, expensive, and large. Thus large processors based on advanced DSP's are unrealistic for miniature portable applications such as PDA's. On the other hand, analog is obviously necessary as the final interface to medical devices and analog also has a great advantage in terms of power dissipation.

Although mimicking biology with analog silicon devices is fascinating it is nevertheless hard to sell to industry. However, medics are showing the most interest, e.g., the cochlear implant, retinal implant, and other types of neural stimulators. Other examples are low-power implantable diagnostic devices to measure blood sugar levels, EEG, ECG, and perceptible stents, IRIS identification, analog MP-3 players, and tele-home-care monitoring for the elderly. The cochlear implant has typically 8-16 electrodes with 250 nW per pole or a total power dissipation of 4-5 microW.

Future research areas include true mixed-signal design environment and interfacing standards, as well as the introduction of software to the analog world (like the analogic cellular computers)

Dean Scribner

There are many image preprocessing issues that arise when a sampled, analog image is readout from an advanced infrared imaging array. Potential solutions have been inspired by biological research on the retina and visual cortex. Work at NRL has focused on the study of retina-like preprocessing techniques as they pertain to several areas.

Specifically these areas are adaptive nonuniformity correction that arises because no two detectors respond exactly alike. Differences in offset, gain, and linearity can lead to spatial noise. Similar nonuniformity effects most certainly occur within the retina, but are "corrected" by subsequent stages of neural processing. Dynamic range management and image compression is also of concern because in IR imaging arrays the charge storage capacity of each unit cell in the readout is limited compared to the potential signal that can be integrated in one frame time. An adaptive dynamic range management schemes are being designed that

achieve near optimum signal integration while maximizing the SNR. Color vision techniques can also be applied to multiband infrared images. In infrared sensors, the probability of detecting objects in cluttered backgrounds can be very poor even though the sensors are performing near their ideal limit of sensitivity. Intuitively, it is expected that the use of information from multiple IR bands should improve performance. Color processing algorithms are under development which greatly improve object/background separation capabilities based on neural processing techniques. Optical flow for hyper-acuity is the ability to precisely compute optical flow in an image sequence and thus allows for autonomous motion detection and image stabilization as well as multiframe processing for increased sensitivity and resolution. Similar forms of processing are believed to be performed in the visual cortex.

Another major effort under way at NRL is the use of IRFPA multiplexer technology for supporting intraocular retinal prosthesis. A collaboration has existed with Johns Hopkins University Hospital for several years and fabricated a microelectronic device has been fabricated that is currently going through preliminary testing. Also has part of this effort, new nano-scale electronic interfaces will offer great improvements in ultra-low-power electrodes for prosthesis and scientific studies of neural tissue.

4.2 Appendix B - Workshop Agenda

Day 1: June 19, 2001

9h00-9h45 *Opening session*

- Welcome by Tamás Roska (SZTAKI), Chairman
- Simon Bensasson (FET head of Unit)
- Carl Smith (EIA division, NSF)
- Remi Ronchaud (ERCIM, EU/NSF co-ordinator)

9h45-12h15 *Session A - Sensing, interfaces, and sensors*

Chair: R. Norman, Reporter: S.Picaud

Presenters: C.Bessant, A.Engel, M.Grattarola, S Picaud, P. De Maziere (M.Van Hulle)

- Bioelectronic, biomechanical and biochemical sensing, as well as brain imaging
- Electronic, mechanical, thermal, chemical and other interfaces to living tissues
- Content and context dependent sensing and sensors, Plasticity

12h15-12h45 *Session Conclusion Discussion*

14h00-17h00 *Session B -Human-machine interaction with autonomous sensors - prostheses*

Chair: R. Eckmiller, Reporter: R. Tetzlaff

Presenters: D.Kipke, K.Lehnertz, P.Rousche, R.Tetzlaff, G.Dorfner, A.Dittmar

- Vision, hearing, tactile and other prostheses
- Implanted alarm devices and acting mechanisms
- Human interactive command without keyboard
- Human aspects

17h00-17h30 *Session conclusion discussion*

17h30-18h00 *Day 1 Conclusion discussion*

Day 2: June 20, 2001

9h00-12h00 *Session C - Bio Systems*

Chair: J. Hámori, Reporter: A.Moschovakis

Presenters: J.Hámori, A.Moschovakis, L.Fortuna, V.Gál, T. Roska

- Motor Control
- Sensor-motor integration
- Integrated sensing-processing-acting and learning devices and technologies
- Ethical issues

12h00-12h30 *Session conclusion and discussion*

14h00-17h00 Session D - Bionic devices

Chair: F. Werblin, Reporter: D. Scribner

Presenters: F.Werblin, N.Francescini, G.Indiveri, Á.Rodríguez-Vázquez, Ch.Toumazou, D.Scribner

- Representation of real-world stimuli in biological systems
- Complex systems – Bio-inspired/ neuromorphic, spatial-temporal computing models with possible programmability
- VLSI implementations and Bionic Eye, Ear, Nose, Skin and other bionic devices

17h00-17h30 Session conclusion and discussion

17h30-18h00 Day 2 Conclusion discussion

Day 3 : June 21, 2001

9h00-12h00 Session E - Assessment of Near Future Directions

Chair: T. Roska and F. Werblin

The main conclusions of Sessions A-D had been assessed and discussed to provide the final results of the workshop (final report), which are meant to serve as a basis for future programs and collaboration between the EU and the NSF. These results will also be circulated in the scientific community for discussion and comments.

12h00-13h00 Round Table (T. Roska Chairman)

- Simon Bensasson (European Commission)
- Carl Smith (National Science foundation)
- Jean-Eric Pin (ERCIM)
- Pekka Karp (European Commission)

4.3 Appendix C - List of Participants

Bensasson, S (FET Head of Unit, European Commission)
Bessant, C (Cranfield University at Silsoe, Bedfordshire)
Dittmar, A (INSA de Lyon)
Dorfner, G (University of Vienna)
Eckmiller, R (University of Bonn)
Engel, A (Inst. of Medicine, Research Centre Juelich)
Fortuna, L (University of Catania)
Franceschini, N (Laboratory of Neurobiology, CNRS)
Gál, V (Neuromorphic Information Technology Postgraduate Center, Budapest)
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Hámori, J (Neurobiology Research Unit Hungarian Academy of Sciences, Budapest)
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Scribner, D (Navy Research Laboratory, Washington DC)
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Tetzlaff, R (Goethe University)
Toumazou, Ch (Imperial College London)
Van Hulle, M / De Maziere, P (Catholic University Leuven)
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4.4 Appendix D – Abstracts and CV of the Participants

in alphabetical order

Dr Conrad Bessant
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Short CV

Originally trained in pure physics, Dr Bessant pursued a PhD in sensors, using a novel combination of data analysis (chemometrics) and electrochemistry to produce a system capable of simultaneous determination of aliphatic compounds in mixtures. Postdoctoral work, carried out at Bristol University (UK), and at Cranfield University focussed exclusively on chemometrics. In his current position, as Lecturer in Computational Methods at Cranfield University, Dr Bessant leads a group developing new algorithms for the interpretation of data obtained from chemical sensors. Application areas include medical and environmental diagnostics.

Key words

Sensors, biosensors, chemometrics.

Abstract

Present the directions, problems, challenges and opportunities you believe your research activity will be facing in the years to come: (i.e.: specific research areas where additional research is needed, where major breakthroughs are expected...)

Chemical sensing is an area where humans and animals invariably outperform machines. For sniffing out controlled substances at customs points, dogs are still the tool of choice, as their olfactory apparatus is more sensitive, more reliable, and more compact than any equivalent man-made gas sensor. Similarly, the human tongue can differentiate between more flavours and dissect complex mixtures more quickly than a laboratory analyser. For detailed quantitative analysis, laboratory instruments have an important role, but for many of the more frequent analyses, such as screening disease, or identifying a pollutant, a more efficient solution is required.

In recent years there have been moves to design sensor systems based on, or even including components from, sensing systems found in nature. A prime example is biosensors – the use of biological sensor recognition elements in an artificial system (e.g. use of an enzyme or antibody coupled to an electrochemical transducer). Other methods mimic biological systems, either by artificial fabrication of recognition elements (e.g. molecularly imprinted polymers) or by using a mechanical analog of a biological system. The ‘electronic nose’ is an important example of the latter. This uses an array of sensors, much like the array of cells in the mammalian nose, coupled to pattern recognition software that is typically based on a computer simulation of the neural network processes occurring in the brain.

These life-like chemical detection systems have proved commercially successful in specific niche areas, such as blood glucose monitoring and wine authenticity testing, but there remain a number of obstacles to their widespread use. The principal challenges are miniaturisation, accuracy, sensor stability, and resilience to interferents. Possible approaches to these challenges include miniaturisation of laboratory systems, and integrated development of sensor hardware and data analysis algorithms.

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Short CV

Born 1961, Villingen, Germany

Academic Education:

1979-1982	Medicine, Basic Sciences, Saarland University, Homburg, Germany
1982-1986	M.D., Medical School, Technical University, Munich, Germany
1983-1987	Ph.D., Neurobiology, Max-Planck-Institute for Psychiatry, Munich

Professional Experience:

1987-1995	Post-Doctoral Fellow, Max-Planck-Institute for Brain Research, Frankfurt, Germany
1996-2000	Heisenberg-Fellow, Head of Research Group, Max-Planck-Institute for Brain Research, Frankfurt
1997-1998	Daimler-Benz Fellow, Institute for Advanced Study Berlin, Germany
2000-present	Senior researcher and Head of Research Group, Research Centre Juelich, Juelich, Germany

Research Interests:

In-vivo neurophysiological approaches to neural network function (microelectrode recording; EEG); information processing in the visual system; dynamics of distributed sensory representations; intermodal and sensorimotor integration; computational theories of perception and representation

Key words

Neural dynamics; real-world cognition; action-oriented approaches; neural synchrony; neural assemblies

Abstract

Neurobiological and neurocomputational research of the past two decades has provided very convincing evidence that studying the temporal dynamics of neural systems may be one of the keys to understanding the biological basis of cognition. I suggest to discuss future challenges in the field of neural dynamics with respect to possible goals, useful experimental strategies and required technical developments.

Key objectives for future project on neural dynamics are (i) the investigation of neural dynamics in more realistic behavioural contexts, in order to approach the basic aspects of real-world cognition; (ii) a conceptual paradigm shift away from the classical representationist framework toward action-/behavior-oriented approaches; (iii) a consequent deconstruction of the serial-hierarchical picture of the brain by emphasizing the role of top-down mechanisms, cross-system interactions, and intermodal binding.

Achieving these objectives will require the design of new experimental strategies that very likely have to include (i) the usage of more realistic stimulus setups and complex sensorimotor paradigms; (ii) experimentation on unrestrained subjects/animals with endogenously controlled and self-paced behavior; (iii) reinforcing complementarity of human and animal studies; (iv) complementing neurocomputational models by building artifacts for real-world and real-time testing of hypotheses.

Implementation of these strategies will, in turn, rest on successful development of new research technologies that allow (i) the monitoring of complex behaviors in realistic environments; (ii) the massively parallel recording of neural signals at the cellular level; (iii) the observation of neuronal dynamics in complex action contexts over extended periods of time, and (iv) the analysis of high-dimensional data sets.

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Short CV

Luigi Fortuna received the degree of Electrical Engineering (cum laudae) from the University of Catania in 1977. Since 1994 he is Full Professor and he teaches System Theory, Adaptive Systems, Biomedical Engineering. He is the coordinator of the courses in Electronic Engineering, the Ph-Degree courses in Electronics and Automation and the Master School in Microelectronics at the University of Catania. He has published more than 250 technical papers and is coauthor of six scientific books in english and several European Patents. His scientific interests include: Robust Control, Nonlinear Science and Complexity, Chaos, Cellular Neural Networks, Soft-Computing Strategies, Robotics, Microsensor and Smart Devices. Prof. Fortuna coordinates the activities among the University of Catania and various Research Consortiums and Companies such as ST Microelectronics. He served as Associate Editor the IEEE Trans. CAS. He is the local responsible of two EU projects: called Clawar and DICTAM, as well as of several R&D projects with international academic and industrial partners. He is Fellow of the IEEE CAS Society.

Key words

Cellular Neural Networks (CNNs), Central Pattern Generator (CPG), biologically inspired locomotion, Dna chip

Abstract

Great interest in research should be paid in the next future to distributed nonlinear arrays for biologically inspired models and data processing

The following two themes deserve particular attention:

1. Implementation of CPGs for biologically inspired motion control using CNNs

A biologically inspired approach is used to realize artificial locomotion in mechatronic devices. The task has been realized by using a particular model of Reaction-Diffusion Cellular Neural Networks generating autowave fronts as well as Turing patterns. Moreover a programmable hardware CNN structure was developed in order to model, generate and control in real time some bio-robots. The programmable hardware implementation gives the possibility to generate locomotion in real time, and also to control the transition among several types of locomotion, with particular attention to hexapods, ring worm-like robots and lamprey-like robots. The approach proposed allows not only to design walking robots, but also to build structures able to efficiently solve typical problems in industrial automation, such as on-line routing of objects moved on conveyor belts.

2. CNNs can allow a fast gene identification by using DNA chips

A new technique, based on Cellular Neural Networks, for DNA-chip automatic analysis will be presented. The approach proposed aims to achieve automatic real-time classification of fluorescence images obtained from DNA microarray after the hybridization process. The paper introduces the main issues in state-of-the art technologies and reports the idea of CNN processing in this field. In particular the key features of this application are reported, together with the description of a sample CNN algorithm and simulation results

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CV

Nicolas Franceschini graduated in Physics, Electronics and Control Theory from the National Polytechnic Institute, Grenoble. He then studied Biophysics and Neurophysiology at the University and Max-Planck Institute for Biological Cybernetics, Tübingen. He received the doctor degree from the National Polytechnic Institute, Grenoble, 1972, and became a staff researcher at the Max-Planck Institute. In 1980 he set up a Neurocybernetics Research Group at C.N.R.S., Marseille, France, and his present position is CNRS Research Director. His research interests cover neural information processing, vision, sensory-motor control, neuromorphic circuits, micro-optics, and bio-inspired terrestrial and flying robots. Since the mid 80's he contributed to the development of the field of «Biorobotics». In 1992 he was awarded the International Louis Vuitton/Moët/Hennessy Science Prize and since 1996 he has been a member of the Academia Europaea. Lately he was involved in the definition of the EU programmes on « Neuroinformatics » and « Bionics ». Some of the seeing robots constructed in Franceschini's laboratory participated in several International Bionics Exhibitions in Europ.

Key words

Neural signal processing, insect vision, bio-inspired sensors, seeing robots, micro air-vehicles

Abstract

Over the past 10 years there has been an increasing tendency to look at biology to find out how to design smart robots and vehicles. In some cases both the biological principles and the art of signal processing have been transcribed into electronic hardware to develop autonomous mobile robots, the processing architectures of which depart considerably from the mainstream AI approach to mobile robotics. Many innovations owe their existence to Arthropods (insects, crustacea, arachnids...), which were largely dismissed in the past as being dumb invertebrates just capable of making stereotyped maneuvers. In fact these apparently humble representatives of life often attain a level of behavioral performances (think of the dragonfly pursuing a mosquito on the wing), beside which both humans and present-day mobile robots look quite puny. Insects can sense, process and act, and their sensory and motor systems are remarkable feats of integrated optronics, neuronics and micromechatronics. They can teach us shortcuts to attain really smart, parsimonious sensory-motor intelligence. Even though neural networks of insects are highly complex they can be analysed with microelectrodes at the level of single, identifiable neurons. The relatively good knowledge gained over the past three decades on insect's sensory-motor abilities and on their neuronal substrates provide us with a rich source of inspiration for tomorrow's intelligent vehicles and micro-vehicles, which will have to cope with unforeseen events on the ground, under water, in the air, in space or in the human body. It is likely that, as we learn more about the parallel, analog and asynchronous processing carried out by nervous systems in general, we will be able to design even better micromachines than what Nature has to offer. Challenging interections are emerging nowadays between the field of sensory-motor neuroscience and the designing of intelligent machines, and this spirit of interchange ought to be fostered. In dealing with both sciences together at the laboratory we have experienced personally how both neuroscience and IT can be furthered at one and the same time. To permit the emergence of bio-inspired IT applications:

- long term research funding is crucial, because transdisciplinary work is akin to risk and long time constant
- curiosity-driven research should not be dismissed as there is no way to identify in advance which particular feature may give rise to IT applications
- the research system in each country should stop deterring young investigators from undertaking transdisciplinary work and should offer them decent career prospects.

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Short CV and an overview of my research activities and fields of interests

2000 – Full professor of Bioelectronics

1984 –2000 Associate professor of Bioelectronics

1977 – 1984 Assistant professor

1976 –1977 Visiting researcher (Temple Univ., Philadelphia, USA)

1975 “Laurea” degree in Physics (summa cum laude)

My research activities include : Neuroengineering : interfacing networks of neurons to arrays of microelectronic devices. Cellular engineering :silicon-based sensors and their application to monitor the cell microenvironment. Nanobiotechnology : use of atomic force microscopy. On the above topics I contributed to more than 70 papers published on international journals. I am co-author (with G. Massobrio) of the book: “Bioelectronics Handbook : MOSFETs, Biosensors, Neurons” McGraw-Hill, ISBN # 0-07-03174-6, 1998.

Key words

Bio-artificial; networks of neurons; training; artificial body; plasticity

Abstract

The direction of the research activity of my Group (WWW.bio.dibe.unige.it) in the near future can be summarized by a statement as follows :

To be able to train in vitro networks of neurons to control artificial bodies towards the accomplishment of specific tasks.

In a broad sense this research should extend the research areas of brain –computer interfaces, in which nervous signals are used to control external devices and that of neuro-prostheses, in which artificial devices directly stimulate the nervous system.

The extension consists in the fact that , while in the above mentioned approach artificial devices are intended as substitutes of missing or damaged brain functionalities, our research intends to use in vitro networks of real neurons as information processing tools. This research has been partially stimulated by the pioneering study very recently started in USA (Chicago’s Northwestern University) and consisting in the control of a roving robot by the brain of a simple organism (i.e. a lamprey, http://www.newscientist.com/news/news-_224233.html).

One of the main challenge of our research will be the development of stimulation protocols (both electrical and neuropharmacological) appropriate to create, thanks to the enormous plasticity properties of the networks, sub-networks of input neurons and of output neurons. The achievement of this result will represent a fundamental step forward both in the understanding of brain functions as well as in the inspiration of new neurobiology-driven formal neural network and neuromorphic devices.

There are two possible long term breakthroughs to be expected : a) Computers which learn from their own experience. b) Brain control of artificial bodies.

Further research will be certainly needed: to design an optimal microenvironment for the networks so to use them for a long period (months, a big improvement over the lamprey short term experiment); to generate input and output neurons. Neurons with high synaptic plasticity will be needed, such as neurons from the brain of mammalian embryos.

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Short CV

Giacomo Indiveri is a Research Assistant at the Institute of Neuroinformatics of the Swiss Federal Institute and the University of Zurich. He graduated in electrical engineering from the University of Genoa, Italy in 1992 and won a post-graduate fellowship within the "National Research Program on Bioelectronic technologies" from which he graduated (cum laude) in 1995. From 1994 to 1996 he worked as a Postdoctoral fellow in the Dept. Biology at the California Institute of Technology, of the design of analog VLSI subthreshold neuromorphic architectures for low-level visual tasks and motion detection. Indiveri is co-teacher of two classes on the analysis and design of analog VLSI Neuromorphic Systems at the Swiss Federal Institute of Zurich and co-organiser of the Workshop on Neuromorphic Engineering, held annually in Telluride, Colorado. His current research interests include the design and implementation of neuromorphic systems for modelling selective attention neural mechanisms, and for exploring the computational properties of networks of silicon integrate and fire neurons.

Key words

neuromorphic circuits, hybrid analog/digital VLSI, perceptive systems, selective attention

Abstract

Neuromorphic engineering is concerned with the design and fabrication of artificial neural systems, such as vision chips, head-eye systems, and roving robots, whose architecture and design principles are based on those of biological nervous systems. The neuromorphic engineering research community has reached a fairly mature knowledge base for the design and development of analog VLSI single-chip sensory systems. The challenges that we face in the immediate future include:

- Sensory fusion
- Physical (analog/digital VLSI) learning systems
- System integration

To accomplish the tasks listed above, we should focus our research on the following topics:

- Development of infrastructure for the design of neuromorphic multi-chip systems
- Integration of single and multi-chip sensory systems with actuators and motors
- Design of (simple) learning software/hardware systems for controlling basic behavioural tasks
- Design of neuromorphic sensory-motor systems able to accomplish pilotage, navigation and foraging

Additional research must be carried out in multidisciplinary teams that combine conventional engineering methods, such as control theory and information theory, with research on conventional neuroscience topics, such as learning, behaviour and perception.

Major breakthroughs are expected in tasks that require engineered systems to survive in and interact with natural environments (e.g. human-machine interfaces, autonomous robots that operate outdoors, etc.).

One effect of this research will be to steer the IT market toward robust, computationally efficient brain-like processors.

The main problems we are faced with include the reluctance of industry to invest in research and development of neuromorphic systems (this is why state/public funding is so important for this field), and the difficulty to find and organise true multidisciplinary research under one roof.

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Short CV

I received a PhD in Bioengineering from the University of Michigan in 1991 and then accepted a faculty appointment at Arizona State University. I lead a large research group in bioengineering and applied neuroscience. Our work is supported by the US-NIH, US-DARPA (defense department), and several private foundations.

The overall goal of my research program is to develop safe and effective neural implants that provide permanent, reliable, and high-capacity information channels (electrical and chemical) between the external world and brain, and then to use these devices as the cornerstone for advanced sensory and motor neuroprosthetic systems. This is an interdisciplinary endeavor that draws on a number of active collaborations from electrical engineering, systems science, materials engineering, neuroscience, biology, and medicine.

Key words

BioMEMS, Neuroprostheses, Plasticity, Sensory replacement, Motor control

Abstract

Advances in neural implants and neuroprosthetic systems have the potential to enable revolutionary medical and scientific advances in the next decade. The brain is becoming more accessible and controllable on almost every level; the challenge lies in directing this potential to gain fundamental new insight into brain function that leads to medical and scientific advances. At least three related research directions are central to the realization of novel “bionic” systems: (i) development of advanced implantable microdevices to establish long-term, bi-directional, and selective interface with neural circuits, (ii) development of real-time system and signal processing structures that utilize the enhanced sensing and actuation capabilities of the neural implants, and (iii) development of techniques to control and exploit neural plasticity. The field is poised to make breakthroughs in each of these areas.

Over the next 5-10 years, developing the next generation of neural implants will present several interesting research challenges and opportunities. While BioMEMS (micro-electromechanical systems) provides the basic technology, it is becoming increasingly clear that existing BioMEMS devices are not sufficient for achieving the level of long-term neural interfaces that will support future neuroprosthetic systems. The major challenges are to: (i) control the biological response to an implant in order to achieve a high level of tissue integration or biocompatibility, (ii) provide hybrid functionality that consists of chemical sensing and delivery, as well as electrical sensing and stimulation, (iii) interface with the nervous system at many scales, from circuits to cells to genes, (iv) achieve the density and placement of active sites that are appropriate for particular applications, and (v) integrate the implantable microdevice with sufficient circuitry for communication with external signal processing and control systems. There are very real opportunities for meeting these challenges by focusing research efforts on the relevant inter-disciplinary areas of science and engineering. For example, appropriate surface modifications of a basic BioMEMS device (silicon or polymer substrate) is a likely mechanism for controlling the biological response to the implant. Integrating microfluidic channels into the design of an existing microelectrode array provides hybrid chemical and electrical functionality. In both of these examples, scientific and engineering studies must be coordinated in order to achieve truly effective new technologies.

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Short CV:

Born in Duisburg, Germany on October 20, 1960. In 1985, diploma degree in physics from the University of Münster. Until 1990 research fellow at the Dept. of Experimental Audiology, Univ. Münster (Biomagnetism and Biosignal-Analysis). Since 1990 research fellow at the Dept. of Epileptology, Univ. Bonn (Nonlinear Time Series Analysis). In 1998, Ph.D. in physics from the Inst. of Radiation and Nuclear Physics and the Dept. of Epileptology, Univ. Bonn. Since 1997 head of the Neurophysics research group at the Dept. of Epileptology, Univ. Bonn

Key words:

Epilepsy, Seizure Anticipation, Seizure Prevention, Nonlinear Dynamics, EEG

Abstract:

Epilepsy is a disorder of the central nervous system. Approximately 1 % of the population suffers from epilepsy, making it one of the most prevalent neurological diseases. Epilepsy is characterized by recurrent seizures, a sudden and highly synchronized discharge of neurons, which may occur in virtually every cortical region. In certain patients the region of the brain that primarily generates seizures can be removed by surgical intervention, which however, may come at the expense of neuropsychological deficits. Other patients require long-term treatment with antiepileptic drugs, that might cause cognitive or other neurological deficits. Although, if it was possible to anticipate the currently assumed random occurrence of epileptic seizures therapeutic possibilities would dramatically change. The search for the hidden information in brain electrical activity predictive of an impending seizure has a long history. However, previous attempts failed to define a pre-seizure period that is long enough to interfere with the development of a seizure. Several lines of evidence now indicate that particularly nonlinear time series analyses of brain electrical activity allow to define a long-lasting pre-seizure period. Although promising, sensitivity and specificity of analysis techniques are not yet sufficient to allow broader clinical application. Nevertheless, since currently available techniques allow a differentiated characterization of the epileptogenic disturbance, the combined use of these techniques along with appropriate classification schemes is regarded a promising venture. Further optimization and development of a miniaturized analyzing system are definitely necessary. Taking into account the technologies currently available, realization of such systems can be expected within the next few years.

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Short CV

Graduated with the M.D. degree from the Medical School of the University of Athens in 1979 and the Ph. D. in the Neurosciences from the Washington University in St. Louis in 1987. Research fellow of the Albert Einstein College of Medicine in New York and Staff Fellow of the Laboratory of Neural Control of the NINDS (NIH). Director of the Division of Computational Neuroscience of the Institute of Applied and Computational Mathematics of FO.R.T.H. (since 1998) and of the Graduate Programm in the Neurosciences of the University of Crete (1994-2001). Section Editor for Neurophysiology and Computational Neuroscience of Brain Research Bulletin (since 1994) and co-director of the Crete Course in Computational Neuroscience (1995-1998). Author or co-author of more than 40 papers and about 30 contributions to conference proceedings focusing on the oculomotor system (employing intraaxonal recording of spike trains in the alert, behaving monkeys) electrophysiology and synaptic physiology of the brain stem, vestibular system, basal ganglia and spinal cord (using fictitiously locomoting cats), computer assisted quantitative morphology (studying the space filling properties of single neurons and groups of neurons of the brain stem and spinal cord) and computer assisted neuronal modeling (building compartmental models of neurons and studying the emergent properties of dynamic pattern generating networks).

Key words

Oculomotor system, compartmental models, dynamic neural networks, gaze control, central pattern generators

Abstract

A major characteristic of the Brain (including the sensoria that feed it information about the world) is that it obeys organisation principles at several scales of physical size (in the sense of a progression from big to small such as the following: network, nucleus, single cell, cellular process, individual synapse, neurotransmitter molecule) simultaneously. The same is true of the behaviors it controls. For example, gaze control can be thought of as control of eye position, head position, body position, etc. In turn the control of eye position is subserved by the saccadic system, the smooth pursuit system, the vergence/divergence system, the VOR and the OKN. Each one of these subsystems is made of a number of central pattern generators (for example, the saccadic subsystem is made of the burst generator, the neural integrator, etc.). Each subsystem is subserved by networks spreading over several distinct brain areas, comprised of several classes of cells, which are connected in a non-random manner into complex information processing circuits; different cells employ different molecules to communicate to each other, their membrane is spatially distributed in a manner that affects their response properties, etc. Although there is a lot of progress along a broad front that concerns several modalities, organs, effectors, computational problems, cell classes, membrane molecules, etc., progress is usually scale specific. When it comes to the mammalian brain, in general, and that of primates, in particular, there is no examples of complex behavior that is understood at all levels of brain organization (from molecules to networks). Unless enough is known about the brain, it is only by accident that one would engineer machines which take advantage of biological principles of organisation to solve problems such as the mundane ones dealt with efficiently and continuously by higher living organisms. Our experience at the Institutes of Applied and Computational Mathematics and of Computer Science of FORTH is probably typical of the aspirations, challenges, successes and obstacles encountered in several European Academic and Research Institutions. We have organised a small group of scientists coming from different backgrounds (Computer Sciences, Neurophysiology, Biology, Mathematics, Anatomy, Engineering, Functional Brain Imaging, etc.) aiming to understand how the brain controls effectors such as the eyes and the head to actively process visual information and to engineer autonomous robots that can do the same in complex and possibly hostile environments. Surprisingly, the major challenges we face are not conceptual/scientific but political/administrative ones related to resource allocation: 1) Although of varied enough background, the mass of scientists we employ is not yet critical enough for interdisciplinary cooperation to be efficient, deep and dense, 2) "Difficult" techniques (such as intracellular recording in alert behaving animals) are too risky to be routinely employed, 3) "Novel" preparations (such as fictitious behaving animals) are also too risky to be set up side by side with more traditional ones.

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Short CV

Trained in the field of vision, I started on the fly compound eye (Dr Franceschini, Marseille, France) to subsequently switch to the vertebrate retina (salamander: Pr Werblin, University of Berkeley, US; rat: Pr Wässle, MPI, Frankfurt, Germany). In 1995, I joined the laboratory of Pr Sahel (INSERM, Strasbourg, France) to develop a group working on the functional assessment of the retina in vivo and in vitro. The strong interface with the ophthalmology clinic allowed us for instance to record adult human retinal neurones in vitro. The technological platform under development should include in vivo recording of both global and multifocal electroretinograms as well as patch clamp recording of retinal neurones in vitro (cultures, retinal slice or isolated retina). Our current interest is to develop new therapeutic strategies for retinal diseases with a major focus on photoreceptor dystrophies. These strategies currently include photoreceptor transplantation and pharmacological neuroprotection, a project on electric stimulation of the vertebrate retina is also under development.

Key words

retina, physiology, therapy, implant, human

Abstract

In term of bionics as defined by the program, several challenges may face the field of vision in the years to come, the major goals being 1) to build retinal implants that could provide useful visual information to blind people, 2) to use visual information processing to generate new systems for pattern recognition. Furthermore, the retina may also provide an adequate model to develop interfaces between natural systems and stimulators from in vitro to in vivo conditions.

1) Since our aim is to develop new therapeutic strategies for retinal diseases, we are starting a collaborative project on retinal implants. Our objectives concern the functional evaluation of these implants on our in vivo and in vitro models with electrophysiological techniques. In fact, the retina appears as an adequate model to develop interfaces with neuronal tissue since adult retinal neurones can survive in culture for months. First, such a culture could be used to test new products entering in the composition of implants; these products should for instance limit glial proliferation that could progressively hinder electrical contact with the neurones. Second, adult retinal cell cultures could be taken to advantage to define specific protocols to stimulate for long periods either graded potential or spike generating neurones.

2) Human adult retinal neurones also survive in culture for months when prepared from postmortem retina. Since we showed further that they maintain normal physiological features in vitro, this in vitro model should become very valuable to define retinal information processing in the human retina and therefore design adequate stimuli for retinal implants. These data on retinal information processing should also become very useful for system of pattern recognition. In fact, genetically modified mice may soon provide most of the data on retinal function, a consideration that led us to participate to a mouse mutant screening. Digital models of mouse retina may inversely help to predict expected phenotypes of mutant mice and thus direct the production of transgenic animals.

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Short CV

M.S., Ph.D. and D.Sc in EE in Budapest. Telecommunication Research Inst.(1970-), Comp. Aut. Res. Inst (SZTAKI) since 1982, Head of Laboratory (Analogical and Neural Computing), Budapest. Nonlinear Electronics Laboratory and Vision Research Laboratory at University of California at Berkeley (part-time since 1989). Fellow of IEEE, member of the Hungarian Academy of Sci., Academia Europaea (London), Academia Scientiarum et Artium Europaea (Salzburg). Professor of Information Technology, Pázmány University , Budapest

Key words

Analogic cellular computers, nonlinear dynamics, neurocomputing, cellular neural networks

Abstract

For sensing-processing-acting- learning on spatiotemporal analog signal arrays (flows) a new computing paradigm is needed. The CNN Universal Machine is a powerful candidate with a core dynamic spatial-temporal instruction defined by a cellular neural network (CNN). Powerful CMOS implementations, analogic software, and -on-chip sensors are available. This could serve as a common programmable learning platform for many future bionics devices and algorithms.

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Short CV (10 lines) :

As a neural engineer I am interested in the technical development and application of multi-channel biological micro-electro-mechanical systems (**Bio-MEMS**) interfaces for the brain. I am interested in their **clinical** use as a tool for information transfer in auditory or visual neuroprosthetics systems, as well as their use in **basic science** to further elucidate brain function and organization. My research pathway is devoted to the application of new materials and approaches as solutions to the challenging problem of creating smart, stable, long-term brain interfaces. Titles of relevant refereed papers include : '*Single-Electrode Intracortical Microstimulation (ICMS) in Auditory Cortex of Behaving Rat*', '*Bioactive Hybrid Structures for Multi-site, Micro-drug Delivery in the Nervous System*', '*Flexible Polyimide-based Intracortical Electrode Arrays with Bioactive Capability*', and '*Chronic Intracortical Microstimulation of Cat Auditory Cortex using the Utah Intracortical Electrode Array.*'

Key words

neuroprosthetics, cortical implants, multi-channel recording and stimulation

Abstract

Bi-directional, high-density, multi-functional neural interfaces in the central nervous system could offer unique solutions to a host of clinically pathological sensory conditions. By identifying and replacing/assisting key bio-informational elements and pathways, 'smart' devices could seamlessly integrate into existing neural networks to provide increased quality of life and restoration of function for blind, deaf and paralyzed persons. Overcoming significant challenges towards this goal will require a radical paradigm shift from traditional research approaches. **Access:** Traditional 'electrode' design and manufacture must give way to the development/integration of new biological micro-electro-mechanical systems (Bio-MEMS) with bioactive capability and enhanced geometrical forms. **Specificity:** Current techniques have only marginal neurons/device ratios. A target goal of achieving massively parallel, geometrically dispersed, *single* neuron communication best mimics existing biology. Traditional electrical stimulation input techniques might be dramatically improved with more locally restricted biochemical activation techniques. **Identificaton:** Information transfer from the external world to the internal world must be optimized through specific target neuron localization via precise device placement. 'Standard' neuroprosthetics systems should be expanded to include additional interfaces in to-be-identified brain regions mediating learning, memory, or sensory integration. **Control:** Multi-channel, multi-area neural interfaces could be used to create closed loop control systems that would both monitor and activate independent neural circuits as needed. Feedback, feedforward and automatic gain control are a few system parameters which should be incorporated into these systems. Such systems should also optimize existing neural networks and harness their associated computational power. To date, optimal encoding/decoding strategies for multi-neural signal input/output are unknown. Clinically useful, advanced neuroprosthetic systems harness great potential only if significant gains in these target areas can be achieved.

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Short CV

Dr. Scribner has been a Research Physicist in the Optical Sciences Division of the Naval Research Laboratory since 1983. Majoring in physics, he received his Ph.D. degree from Georgetown University, Washington D.C. where his research included the effects of heavy doping on the electronic properties of narrow band gap semiconductors. His current research interests are in infrared detectors, focal plane arrays, and associated image processing techniques. Specific research studies include testing of advanced FPA's, development of image pre-processing algorithms, and algorithms for multiband IR systems. Much of his image preprocessing work and multiband efforts are inspired by an understanding of related mechanisms in biological vision.

Key words

infrared, focal plane array, retina, image processing, neural prosthesis

Abstract

The rapid development of infrared focal plane arrays (IRFPA's) and silicon charge coupled devices (CCD's) over the past 30 years has led to very large format devices and a new generation of infrared systems. Nevertheless, a number of image preprocessing issues remain unsolved at this time. Potential solutions have been inspired by biological research on the retina and visual cortex. In our work at NRL, we have been studying retina-like preprocessing techniques as they pertain to several areas described below.

Adaptive Nonuniformity Correction: One example of an imaging problem with IRFPA's is that no two detectors respond exactly alike. Differences in offset, gain, and linearity can lead to spatial noise. Similar nonuniformity effects most certainly occur within the retina, but are "corrected" by subsequent stages of neural processing. For example, in human retinas measurements show variation in area of the photoreceptors of 10%. At NRL, image pre-processing techniques have been developed to perform adaptive nonuniformity correction of unit cells within an imaging array.

Dynamic Range Management and Image Compression: In IRFPA's, the charge storage capacity of each unit cell in the readout is limited to approximately 10^7 to 10^8 carriers. For a long wavelength infrared sensor with an F/1 lens, a wide spectral band, and a integration time of 33 ms, the number of carriers generated would be roughly 1010. Therefore, the potential signal needs to be attenuated by a factor of 102 to 103 in order to avoid saturation. Can an adaptive dynamic range management scheme be designed that achieves near optimum signal integration while maximizing the SNR.

Color Vision Techniques Applied to Multiband Infrared Images: In infrared sensors, the probability of detecting objects in cluttered backgrounds can be very poor even though the sensors are performing near their ideal limit of sensitivity. Intuitively, it is expected that the use of information from multiple IR bands should improve performance. In biological vision, wavelength is often just as important as intensity for overcoming the effects of camouflage and for finding objects. In this manner we can directly view the rich IR phenomenology inherent in each scene. To display this type of imagery in an intuitive manner, two important biological processing functions are being studied - color constancy and color contrast enhancement. Our focus is to develop algorithms which greatly improve object/background separation capabilities based on neural processing techniques.

Optical Flow and Hyper-acuity: The ability to precisely compute optical flow in an image sequence allows for autonomous motion detection and image stabilization as well as multiframe processing for increased sensitivity and hyperacuity (super-resolution). Similar forms of processing are believed to be performed in the visual cortex.

Another major effort we are undertaking is the use of IRFPA multiplexer technology for supporting intraocular retinal prosthesis. We have been collaborating with Johns Hopkins University Hospital for several years and have fabricated a microelectronic device that is currently going through preliminary testing.

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Curriculum Vitae

March 26th, 1958 born in Frankfurt am Main (Hessen)

1978 final examination (Abitur), Frankfurt

1979-1985 student of physics, mathematics and physical chemistry

1979-1986 at the Johann Wolfgang Goethe-University of Frankfurt/M.

1985 diploma of physics

1990 PhD

1992 assistant professor of applied physics at Frankfurt University

1997 guest researcher at UC Berkeley

1998 habilitation at the faculty of physics

2000 lecturer of physics at the Johann Wolfgang Goethe-University of Frankfurt/M.

2001 visiting senior researcher at the Analogical and Neural Computing Laboratory,
Computer and Automation Research Institute, Hungarian Academy of Sciences
in Budapest

Fields of Work

Theory of signals and systems, stochastic processes, physical fluctuation phenomena (1/f noise), system modelling, system identification, artificial neural networks

Key words

Signal analysis, brain electrical activity, Cellular Neural Networks, prediction, epileptic seizures

Abstract

Several comprehensive investigations showed that the determination of nonlinear measures [1], e.g. estimates of an effective correlation dimension D_2 , can be useful to characterize an epileptogenic process. Especially, Lehnertz and Elger showed that certain distinct changes of D_2 can be regarded as precursors of an impending seizure. Up to now a direct real time calculation of D_2 is not possible since the determination is aligned with a high computational complexity.

In this contribution, we present a new method for the analysis of the spatio-temporal dynamics of brain electrical activity in epilepsy. In order to detect changes occurring minutes before seizure onset invasive multichannel recordings of brain electrical activity will be analyzed with Cellular Neural Networks (CNN).

CNN [2] are a unified paradigm for many applications, such as image processing, modelling nonlinear spatio-temporal systems, or modelling complex phenomena. Realizations of the CNN universal machine have the capability of supercomputer, allowing trillion of operations per second in a single chip. In this paper, we consider CNN for the approximation of the D_2 measure. Furthermore, we present new CNN based methods for the detection of precursors of an impending seizure. Our results show that in many cases a reliable detection can be performed with CNN in real time allowing the realization of a mobile miniaturized system for the anticipation of seizures.

[1] Lehnertz, K., Andrzejak, R.G., Arnhold, J., Widman, G., Burr, W., David, P., and Elger, C.E.: Possible Clinical and Research Applications of Nonlinear EEG Analysis in Humans; Proc. Workshop Chaos in Brain, World Scientific 1999, pp.134-155

[2] Chua, L.O.: CNN: A Paradigm for Complexity; World Scientific 1998

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Short CV

Chris Toumazou, PhD, is a Professor of Circuit Design in the Department of Electrical and Electronic Engineering, Imperial College, London, U.K and a Fellow of the IEEE. He received his PhD from Oxford-Brookes University in collaboration with UMIST Manchester in 1986. His research interests include high frequency analogue integrated circuit design in bipolar, CMOS and SiGe technology for RF electronics and low-power electronics for biomedical applications. He has authored or co-authored some 300 publications in the field of analogue electronics and is a member of many professional committees. Chris has 7 patents in the field of RF and low power electronics. Chris is currently head of the Circuits and Systems Group with the Dept of EEE and the Head of the Dept. of Biological and Medical Systems at Imperial College.

Key words

perceptive analog processing, advanced mixed signal, micropower modelling.

Abstract

Problems:

Increased DSP functionality causes power consumption to rise to levels which are unrealistic for miniature portable applications such as PDAs etc. the development of large scale parallel processing networks leads to problems of data transmission between chips and between subsystems in system-on-chip (SOC) implementations.

Directions:

Silicon to replace biology, and silicon inspired by biology. Micropower analog implementations of digital algorithms for perceptual applications, giving significant power savings.

Challenges:

Developing technology-independent analog design. Developing true mixed signal design tools and methodologies. Operating micropower analog embedded within digital SOC.

Opportunities:

Exploiting device physics (MOS subthreshold) to achieve very low power operation. Application areas include: low power sensor interaction e.g. MEMS, biosensors: invasive and non-invasive biomedical devices.

Major breakthroughs:

Replacing digital software and hardware with analog hardware for dramatic reductions in power.

Research areas include:

Development of true mixed-signal design environment. Improved device modelling for CMOS subthreshold region. Development of interfacing standards for mixed-signal SOC design.

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Born in Ghent, Belgium, on 6 April 1960
Phd. in Applied Sciences, K.U.Leuven, Leuven, Belgium, 1990
Master of Engineering Sciences in Electronics, K.U.Leuven, Leuven, Belgium, 1985
Master of Business Administration, LUC/EHL, Diepenbeek, Belgium, 1991
Associate Professor (Hoofddocent) K.U.Leuven, teaching Neural Computing and Visual Neuroscience
Director and founder of Synes N.V., K.U.Leuven spin-off

Research activities:

Neural networks, fMRI analysis tools, computational neuroscience, non-linear signal processing.
Research is funded by grants received from European Commission (Quality of Life), Belgian Federal and Flemish government, and industry

Fields of interest:

visual neuroscience, neural networks, fMRI

Key words

magnetic resonance scanners, fMRI, neural networks, signal processing,

Abstract

One of the most promising neuro-imaging techniques, for both diagnostic as well as basic brain research purposes, is functional magnetic resonance imaging (fMRI), since it is non-invasive, and since the recorded signal is a more direct measure of metabolic activity. Current statistical tools for analyzing fMRI data are aimed at investigating the relationship between the experimental paradigm and local changes in brain activity. They assume that the voxels in the discretized brain image are independently and identically distributed and, thus, that they obey univariate statistics. However, since cognitive functions result from interactions between brain regions, the independence assumption is likely to be invalid. The challenge for the future is to develop new concepts and tools that consider the active brain regions as part of a network, possibly with recurrent and task- or condition-dependent connections. Due to the extremely low signal-to-noise-ratio of the recorded fMRI signals, the occurrence of artefacts, such as the cardio-respiratory ones, and their non-stationary and non-Gaussian behavior, additional research in signal processing, computer vision, statistics, and network modelling is needed before such tools can be developed. Furthermore, one should be able to constrain the network model by the known anatomy of the connections, or by the expected connectivity for a given neurological disease, or by some other prior.

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Short CV

Prof Frank S. Werblin, Professor of Neurobiology, Department of Molecular and Cell Biology, University of California at Berkeley, Berkeley CA 94720. BS,MS Elec Eng MIT 1960 ; PhD Johns Hopkins Univ 1968 ; Prof Elec Eng, UC Berkeley 1970-1985 ; Prof Neurobiology, Molec Cell Biol UC Berkeley 1976-now.

Research Activities:

Studies of biological image processing in mammalian retina with emphasis on the forms of representation expressed by biological systems in response to natural scenes. Circuitry and algorithmic basis for biological vision. Implementation of biological vision algorithms in silicon, specifically implemented in Cellular Nonlinear Network architecture.

Key words

retina, vision, neural computation, artificial vision, cellular nonlinear network.

Abstract

Our recent studies show that there exists a set of about a dozen distinct simultaneous dynamic representations of the visual world (12 movies) formed in the retina through complex neural interactions, and then carried intact to higher visual centers. These representations form a feature space with its own forms of inhibitory interactions that sharpen up individual features within the space. With this basis, we plan to: 1) follow the further refinement of these features to higher visual centers to understand higher level processing, 2) evaluate the neural mechanisms within the retina that lead to the formation of this elaborate feature space, and 3) try to determine how and why nature selected these features to fully represent the visual world. In addition these features form the natural language of mammalian vision, which could be used to activate the brain in any prosthetic regime. We are developing the technology to generate these feature detectors in CNN silicon technology as part of a prosthetic vision front end system. The breakthroughs will lie in the discovery of the principles of operation whereby the visual world is efficiently represented in neural space, and in the development of CNN-based technology that will efficiently implement biologically-inspired algorithms for a variety of image processing applications. It is our hope that these studies will set a precedent for understanding image processing in a variety of sensory systems, and will lead to implementation of silicon-based technologies that are deeply biologically inspired.

Present the directions, problems, challenges and opportunities you believe your research activity will be facing in the years to come: (i.e.: specific research areas where additional research is needed, where major breakthroughs are expected...)

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Short CV

Jimmy Xu (Ph.D University of Minnesota, 1987) is Professor of Engineering and Professor of Physics at Brown University, Rhode Island. Prior to moving to Brown University in 1999, he was Director, Nortel Institute for Telecommunications of The University of Toronto, held the Nortel Chair of Emerging Technologies and was also the James Ham Chair Professor in Optoelectronics. He received six international and Canadian prizes and awards for his research contributions, including the 1995 Steacie Prize of Canada. Seven of his former and current students received international and national prizes for their accomplishments during their thesis works, including two NSERC Doctoral Thesis Medals. He published over 120 articles in refereed journals in the areas of physics, electronics, quantum electronics, nanostructures, photonics, lasers, and chemistry and over 80 conference papers, and gave over 120 invited talks, seminars, presentations and speeches. He served as Editor of IEEE Transactions on Electron Devices 1992-97, Co-editor for three books, and IEEE EDS Distinguished Lecturer 1995-99. He is currently Distinguished Visiting Scientist of NASA Jet Propulsion Lab and a member of the Advisory Board for Information and Communications Technologies of the National Research Council of Canada, a Foreign Associate of the Canadian Institute of Advanced Research, and serves on a number of Advisory Boards of Companies and Firms. His current research interests include Photonics, Nano and Molecular Sciences and Technologies, and Collective Behavior for Computing.

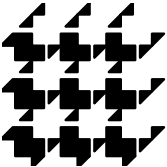
Key words

Collective Behavior for Computing, DNA Engineering, Molecular Electronics, Carbon Nanotubes, Quantum Physics.

Abstract

Let me start with a general position statement, and then put forward a set of more provocative views. Information technology has been a phenomenal success but a narrow one it is so far primarily about information processing and transmission. Information technology needs to evolve into one that is as much about information acquisition and execution as it is about processing and transmission. The time is right, and the conditions are favorable, because the mighty microelectronics technology as the engine driving the information technology evolution along the one-dimensional path of scaling down is encountering major crises and problems. These crises and problems will only get much worse down the road to nanoelectronics. But, on the other hand, they will help the microelectronic technology to broaden its reach into information acquisition and execution and will motivate the search for new or alternative paths.

These crises and problems are not the much feared problems of physical limits in making and operating smaller devices! The real crises are in wiring and power dissipation! And, the big problem is in the diminishing economic returns of CMOS scaling down (to nm scale). All these crises and problems are rooted in our continued dependence on von Neumann binary serial computing paradigm, and in the lack of a sound alternative architecture that is perhaps non-binary, certainly non-serial, and thereby does not demand for more wiring and will dissipate much less heating. Does such an architecture exist? Human brain seems to be one. There may even be some less-obvious ones embedded in or extractable from the collective behaviors of physical systems. What is the actual architecture? How does it compute? or What does it compute? Those are the tough questions and challenges facing us. In this context, I share with many the strong reservations on the fashionable pushes for the development and demonstration of such molecular logic gate as AND, OR, XOR etc., be it man-made carbon nanotubes or biologic molecules or the like. I'd instead advocate for efforts that aim at probing, interrogating, direct or indirectly copying and utilizing the collective behaviors of large ensembles of simple elements, which could be brain neuronal networks or just man-made nanostructure arrays. To aid this advocacy, I will bring in specific examples from our own recent work on brain cortex coupling with nanotube arrays, 'nano-ear' (arrayed nanotube acoustic sensor array), and altering DNA conductivity via ionic 'doping'.



This workshop is part of series of strategic workshops to identify key research challenges and opportunities in Information Technology. These workshops are organised by ERCIM, the European Research Consortium for Informatics and Mathematics, and DIMACS the Center for Discrete Mathematics & Theoretical Computer Science. This initiative is supported jointly by are supported by the European Commission's Information Society Technologies Programme, Future and Emerging Technologies Activity, and the US National Science Foundation, Directorate for Computer and Information Science and Engineering.

More information about this initiative, other workshops, as well as an electronic version of this report are available at the ERCIM website under <http://www.ercim.org/EU-NSF/>

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