Biosystems & Biorobotics

Ana Rita Londral
Pedro Encarnação *Editors*

Advances in Neurotechnology, Electronics and Informatics

Revised Selected Papers from the 2nd International Congress on Neurotechnology, Electronics and Informatics (NEUROTECHNIX 2014), October 25–26, Rome, Italy

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Biosystems & Biorobotics

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Aims & Scope

Biosystems & Biorobotics publishes the latest research developments in three main areas: 1) understanding biological systems from a bioengineering point of view, i.e. the study of biosystems by exploiting engineering methods and tools to unveil their functioning principles and unrivalled performance; 2) design and development of biologically inspired machines and systems to be used for different purposes and in a variety of application contexts. The series welcomes contributions on novel design approaches, methods and tools as well as case studies on specific bioinspired systems; 3) design and developments of nano-, micro-, macrodevices and systems for biomedical applications, i.e. technologies that can improve modern healthcare and welfare by enabling novel solutions for prevention, diagnosis, surgery, prosthetics, rehabilitation and independent living.

On one side, the series focuses on recent methods and technologies which allow multiscale, multi-physics, high-resolution analysis and modeling of biological systems. A special emphasis on this side is given to the use of mechatronic and robotic systems as a tool for basic research in biology. On the other side, the series authoritatively reports on current theoretical and experimental challenges and developments related to the "biomechatronic" design of novel biorobotic machines. A special emphasis on this side is given to human-machine interaction and interfacing, and also to the ethical and social implications of this emerging research area, as key challenges for the acceptability and sustainability of biorobotics technology.

The main target of the series are engineers interested in biology and medicine, and specifically bioengineers and bioroboticists. Volume published in the series comprise monographs, edited volumes, lecture notes, as well as selected conference proceedings and PhD theses. The series also publishes books purposely devoted to support education in bioengineering, biomedical engineering, biomechatronics and biorobotics at graduate and post-graduate levels.

About the Cover

The cover of the book series Biosystems & Biorobotics features a robotic hand prosthesis. This looks like a natural hand and is ready to be implanted on a human amputee to help them recover their physical capabilities. This picture was chosen to represent a variety of concepts and disciplines: from the understanding of biological systems to biomechatronics, bioinspiration and biomimetics; and from the concept of human-robot and human-machine interaction to the use of robots and, more generally, of engineering techniques for biological research and in healthcare. The picture also points to the social impact of bioengineering research and to its potential for improving human health and the quality of life of all individuals, including those with special needs. The picture was taken during the LIFEHAND experimental trials run at Università Campus Bio-Medico of Rome (Italy) in 2008. The LIFEHAND project tested the ability of an amputee patient to control the Cyberhand, a robotic prosthesis developed at Scuola Superiore Sant'Anna in Pisa (Italy), using the tf-LIFE electrodes developed at the Fraunhofer Institute for Biomedical Engineering (IBMT, Germany), which were implanted in the patient's arm. The implanted tf-LIFE electrodes were shown to enable bidirectional communication (from brain to hand and vice versa) between the brain and the Cyberhand. As a result, the patient was able to control complex movements of the prosthesis, while receiving sensory feedback in the form of direct neurostimulation. For more information please visit http://www.biorobotics.it or contact the Series Editor.

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Preface

The present book includes extended and revised versions of a set of selected papers from the Second International Congress on Neurotechnology, Electronics and Informatics (NEUROTECHNIX 2014), held in Rome, Italy from October 25 to 26, 2014.

The purpose of the International Congress on Neurotechnology, Electronics and Informatics is to bring together researchers and practitioners in order to exchange ideas and develop synergies highlighting new advancements of neurotechnology, either in general or regarding a particular case, application, or pathology.

NEUROTECHNIX 2014 was sponsored by INSTICC (Institute for Systems and Technologies of Information, Control and Communication), held in cooperation with MedinRes—Medical Information and Research, Nansen Neuroscience Network, Sociedade Portuguesa de Neurologia (SPN), Associação Portuguesa de EEG e Neurofisiologia Clínica (APEEGNC), Neurotech Network, Societa Italiana de Neurologia (SIN), World Federation for NeuroRehabilitation (WFNR) and the International Neural Network Society (INNS), and in collaboration with The Marketplace for Research Antibodies.

The congress received submissions from 19 countries, in all continents. To evaluate each submission, a double-blind paper review was performed by the program committee, whose members are highly qualified researchers in the NEUROTECHNIX topic areas.

NEUROTECHNIX's program included panels, special sessions, and five invited talks delivered by internationally distinguished speakers: Constantin A. Rothkopf (Technical University Darmstadt, Germany), Danil Prokhorov (Toyota Tech Center, United States), Eugenio Guglielmelli (Università Campus Bio-Medico, Italy); Febo Cincotti (Sapienza University of Rome, Italy), and Hermano Igo Krebs (Massachusetts Institute of Technology, United States).

We would like to thank the authors, whose research and development efforts are recorded here for future generations.

April 2015

Ana Rita Londral
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Contents

From Biological to Numerical Experiments in Systemic Neuroscience: A Simulation Platform

Nicolas Denoyelle, Maxime Carrere, Florian Pouget, Thierry Viéville and Frédéric Alexandre

Abstract Studying and modeling the brain as a whole is a real challenge. For such systemic models (in contrast to models of one brain area or aspect), there is a real need for new tools designed to perform complex numerical experiments, beyond usual tools distributed in the computer science and neuroscience communities. Here, we describe an effective solution, freely available on line and already in use, to validate such models of the brain functions. We explain why this is the best choice, as a complement to robotic setup, and what are the general requirements for such a benchmarking platform. In this experimental setup, the brainy-bot implementing the model to study is embedded in a simplified but realistic controlled environment. From visual, tactile and olfactory input, to body, arm and eye motor command, in addition to vital interoceptive cues, complex survival behaviors can be experimented. We also discuss here algorithmic high-level cognitive modules, making the job of building biologically plausible bots easier. The key point is to possibly alternate the use of symbolic representation and of complementary and usual neural coding. As a consequence, algorithmic principles have to be considered at higher abstract level, beyond a given data representation, which is an interesting challenge.

Keywords Simulation · Computational neuroscience · Virtual reality

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1 Introduction

Computational neuroscience is often presented as a way to better understand the complex relations between structures and functions in the brain. Particularly, these relations are complex because they are not symmetrical: one structure participates to several functions and functions are distributed among many structures. This is an important limitation against developing a model of a structure in isolation, which is often the case in computational neuroscience. This is not sufficient to emulate one behavioral function, but participates only to studying some of its properties, with the risk of neglecting the key influence of another structure on this function. Consequently, for modeling studies interested in integrative and behavioral neuroscience and in the emulation of behavioral functions, this analysis is a plea for designing brain models including many brain structures. In addition, in the framework of studying behavioral functions, the brain must also be considered as a complex system in interaction with the body and the environment. Two important consequences can be drawn. The first consequence is related to the model itself. Additional modules must be considered, to allow for the sensation and processing of signals from the environment (exteroception) and also from the body (interoception). Designing such a network of brain structures and modules at the interface with the outer and inner world includes not only understanding how each subsystem (visual, motor, emotional, etc.) works but also how these subsystems interact as a whole, to yield emerging behaviors, i.e. effects that result from interactions between subsystems. The second consequence is related to the use of this complex system. Studying and validating functional models of brain structures at a macroscopic behavioral scale cannot be performed with restrained artificial static paradigms but requires experiments in complex environments, with realistic sensory-motor tasks to be performed, including high-level interactive behaviors (e.g. survival strategy in the presence of prey/predators) and long-term protocols (since both statistical studies and biologically-plausible learning mechanisms require long epochs). Such paradigms are to be related to biological experiments conducted on animals. These statements are not only characterizing brain models working in interaction with their environment, they also give strong requirements on the tools that must be designed to simulate these models and to experiment them.

Designing such tools is also an excellent way to address at the same time the two main objectives of such brain models at the macroscopic scale. One hand, they are intended to serve neuroscientists as a new platform of experimentation, on which they can apply their classical protocols of observation and analysis of animals at the behavioral as well as electrophysiological levels. It is consequently important that neuroscientists can observe the inner activity of the models, as they use to do for example with electrodes (but we can imagine that this observation in digital models might be more easy than in the real brain). It is also important that they can define classical behavioral protocols like they do in animals (e.g. fear conditioning) in order to observe the resulting behavior and the corresponding brain activation. Defining such protocols implies that the structure of the external world (e.g., maze,

food magazine) as well as its intrinsic rules (e.g. tone followed by an electric shock) should be easy to design.

On the other hand, these tools are also intended to serve computer scientists as a way to design artificial autonomous systems, driven by brain models. In this case, it is important for the supposed properties of the models (e.g., capacity to learn, robustness to noise or changing rules) to be assessed by rigorous evaluation procedures, as it is defined for example in the domain of machine learning. In this case also an easy access must be proposed both to the inner circuitry of the models and to the specification of the external world.

With in mind this double goal of offering convenient tools to both scientific communities, we report in this paper the specifications that we have elaborated and present the corresponding software platform that we call VirtualEnaction. We also introduce the case study of a behavioral function presently under study in our team, pavlovian conditioning, as an illustration of the use of VirtualEnaction. Before that, some more words must be said to justify the need for such a platform.

2 Problem Position

Concerning the nature of such a simulator, real robotic systems are often used and answer particularly well to the second requirement about a realistic environment. However, building viable robotic systems and making them evolve in realistic environments (e.g. natural sites) for long periods of time (e.g. several days) is just too expensive in term of cost and manpower in many circumstances and particularly during early phases of development. Furthermore, the goal of such simulation is not only to make a demo, but also, and more importantly, to study and quantify the behavior of functional models of the brain. As a consequence we not only need a complex, long-term, realistic experimental setup, but we also need a controllable and measurable setup where stimuli can be tuned and responses can be measured. In fact, real environment complexity and parameters are intrinsically difficult when not impossible to control. This is the reason why we propose to use a digital simulator implementing realistic survival and other biological scenarios.

A step further, available macroscopic models of brain functions are not designed for “performance” but to properly implement phenomenological concepts that have been investigated in some cognitive or behavioral framework. They would therefore have “no chance” in a real world. Note that recent computer science mechanisms designed without any constraint regarding biological plausibility but only towards final performances are nowadays probably more efficient but that are not relevant regarding the brain behavior explanation.

As a consequence we also need a setup which can provide a “simplified environment”, for systemic models of the brain at the state of the art not to fail immediately. We must also take into account the fact that (i) such models are rather slow to simulate (unless huge computer power is available), and that (ii) they are

not supposed to focus on precise issues regarding low-level sensory input or motor output but on integrated cognitive functions and the resulting behaviors.

This, in addition to technical constraints, yields three key characteristics:

1. No real-time but a look-and-move paradigm: The main restriction we propose is to have the simulator running at a "slower" time (i.e. using several seconds to simulate one real-time second) and also to consider discrete time sampling. This seems obvious as far as digital simulation is concerned, but in terms of underlying framework, this has several consequences (e.g., giving up the possibility for a human observer to interact with the simulation, restraining to clock-based (and not event-based) dynamical models, etc.) [1].
2. No real robotic control but only motor command: Since in the nervous system motor control seems to be a hierarchical system with high-level motor commands, while their closed loop execution is delegated to the peripheral motor system [2], we may accept to only simulate gesture and displacement at a rather symbolic level such as "stand-up" or "turn 90° rightward". This indeed cancels the possibility to study sharp phenomena of motor interactions with the environment but allows us to concentrate on high-level control such as action selection mechanism and motor planning.
3. Complex but not necessarily natural visual environment: The third main restriction we propose to accept is to consider a complex visual environment (with visual textures, several objects in motion, etc.) but not to invest in the simulation of a realistic natural scene simulation. The reason of this choice is that natural image vision is an issue already well studied [3]. The general conclusion is that biological visual systems are tuned to natural image statistics, decomposed by the early visual front-end in such a way that higher-level visual input only relates on cues orthogonal (in a wide sense) to natural image statistics. In other words, the job regarding this aspect is done by early-vision layers and we may consider more stylistic visual cues at a higher-level. Depending on the study, we may also wish to work on either a pixelic or a symbolic representation of the visual scene. See [4] for details of how the early-visual system implements such dual representation.

3 System Description

We consider that a "brainy-bot", i.e. the implementation of a global model of the brain functionalities, interacts with its environment with the simple goal of surviving. Our objective is to simulate the sensory-motor interactions of this bot with respect to its environment. Examples of such surroundings are shown in Fig. 1.

Survival is precisely defined as maintaining vital variable values in correct ranges, as formalized in, e.g., [5]. In our context, health, food, water, energy, and