

# Real Time On-Chip Implementation of Dynamical Systems with Spiking Neurons

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**Abstract**—Simulation of large-scale networks of spiking neurons has become appealing for understanding the computational principles of the nervous system by producing models based on biological evidence. In particular, networks that can assume a variety of (dynamically) stable states have been proposed as the basis for different behavioural and cognitive functions.

This work focuses on implementing the Neural Engineering Framework (NEF), a formal method for mapping attractor networks and control-theoretic algorithms to biologically plausible networks of spiking neurons, on the SpiNNaker system, a massive programmable parallel architecture oriented to the simulation of networks of spiking neurons. We describe how to encode and decode analog values to patterns of neural spikes directly on-chip. These methods take advantage of the full programmability of the ARM968 cores constituting the processing base of a SpiNNaker node, and exploit the fast Network-on-chip for spike communication.

In this paper we focus on the fundamentals of representing, transforming and implementing dynamics in spiking networks. We show real time simulation results demonstrating the NEF principles and discuss advantages, precision and scalability. More generally, the present approach can be used to state and test hypotheses with large-scale spiking neural network models for a range of different cognitive functions and behaviours.

## I. INTRODUCTION

Construction of large-scale spiking neural models is possible thanks to the emergence of unified approaches that are able to scale up seamlessly. These models can be simulated taking advantage of recent developments in computational infrastructure that can equally be scaled up. Some models aim to find emerging functions from the structural data known from biology. For example, quantitative descriptions of cortex based on anatomical data [4] can be used to model systems that naturally scale up [19], due to the regularity of the laminar organization of the thalamo-cortical system [35]. Other approaches can be considered more functional, where neural dynamics and quantities act as biological constraints in modelling specific cognitive functions [7]. Some functions can be modelled using attractor networks [1], networks that can represent information by settling to a (dynamically) stable state with their self-sustained, persistent activity. For example functions like memory can be associated to brain areas that are believed to use attractor representation such as the hippocampus [37].

Simulating large scale networks of biologically plausible neurons is a challenging task which require scalable compu-

tational and communication resources. Therefore simulations usually take place on supercomputers [2], general purpose hardware as FPGAs [24] or dedicated neuromorphic hardware [28] [36]: every approach has different scalability, programmability, precision and power consumption characteristics.

In this context we describe how to map the principles of the Neural Engineering Framework (NEF) [10], a unified approach for implementing complex neuro-dynamical systems and mapping control-theoretic algorithms with the neural connections between a highly heterogeneous population of spiking neurons, to the SpiNNaker System [13], a massively parallel programmable architecture oriented to the simulation of large scale models of spiking neural networks.

The paper describes the approach taken to encode and decode values directly on-chip, taking advantage of the programmability of the SpiNNaker system and exploiting the fast on-chip spike-based interconnect for communication between neural populations.

We show how a variety of networks can be built using encoding/decoding methods. In short, the approach presents the basis for testing large-scale neural models built with the NEF integrating SpiNNaker as the computational back-end in the existing framework and tools.

The rest of the paper is structured as follows: we introduce the Neural Engineering Framework and the SpiNNaker System in the first two sections. We then present the approach used to port the NEF on SpiNNaker, and present results obtained with the approach in sections IV and V respectively. Finally, discussion about how to expand the work and conclusions are drawn in the last two sections.

## II. NEURAL ENGINEERING FRAMEWORK

The Neural Engineering Framework [10] describes how biologically relevant variables can be encoded and processed in the dynamic neural activity of recurrently connected networks. This approach can be used to introduce complex control theoretic models into spiking neural networks, including standard attractor network models [8]. The NEF is captured by three principles:

- 1) **Representation** in neurons is defined by the combination of nonlinear encoding (exemplified by neuron tuning curves) and weighted linear decoding.

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## **Real Time On Chip Implementation Of Dynamical Systems With:**

Synaptic Plasticity for Neuromorphic Systems Christian Mayr, Sadique Sheik, Chiara Bartolozzi, Elisabetta Chicca, 2016-06-26 One of the most striking properties of biological systems is their ability to learn and adapt to ever changing environmental conditions tasks and stimuli It emerges from a number of different forms of plasticity that change the properties of the computing substrate mainly acting on the modification of the strength of synaptic connections that gate the flow of information across neurons Plasticity is an essential ingredient for building artificial autonomous cognitive agents that can learn to reliably and meaningfully interact with the real world For this reason the neuromorphic community at large has put substantial effort in the design of different forms of plasticity and in putting them to practical use These plasticity forms comprise among others Short Term Depression and Facilitation Homeostasis Spike Frequency Adaptation and diverse forms of Hebbian learning e.g Spike Timing Dependent Plasticity This special research topic collects the most advanced developments in the design of the diverse forms of plasticity from the single circuit to the system level as well as their exploitation in the implementation of cognitive systems

**Artificial Neural Networks and Machine Learning -- ICANN 2013** Valeri Mladenov, Petia Koprinkova-Hristova, Günther Palm, Alessandro Villa, Bruno Apolloni, Nikola K.

Kasabov, 2013-09-04 The book constitutes the proceedings of the 23rd International Conference on Artificial Neural Networks ICANN 2013 held in Sofia Bulgaria in September 2013 The 78 papers included in the proceedings were carefully reviewed and selected from 128 submissions The focus of the papers is on following topics neurofinance graphical network models brain machine interfaces evolutionary neural networks neurodynamics complex systems neuroinformatics neuroengineering hybrid systems computational biology neural hardware bioinspired embedded systems and collective intelligence

Enterprise Digital Transformation Peter Augustine, Pethuru Raj, Sathyan Munirathinam, 2022-02-17 Digital transformation DT has become a buzzword Every industry segment across the globe is consciously jumping toward digital innovation and disruption to get ahead of their competitors In other words every aspect of running a business is being digitally empowered to reap all the benefits of the digital paradigm All kinds of digitally enabled businesses across the globe are intrinsically capable of achieving bigger and better things for their constituents Their consumers clients and customers will realize immense benefits with real digital transformation initiatives and implementations The much awaited business transformation can be easily and elegantly accomplished with a workable and winnable digital transformation strategy plan and execution There are several enablers and accelerators for realizing the much discussed digital transformation There are a lot of digitization and digitalization technologies available to streamline and speed up the process of the required transformation Industrial Internet of Things IIoT technologies in close association with decisive advancements in the artificial intelligence AI space can bring forth the desired transitions The other prominent and dominant technologies toward forming digital organizations include cloud IT edge fog computing real time data analytics platforms blockchain technology digital twin

paradigm virtual and augmented reality VR AR techniques enterprise mobility and 5G communication These technological innovations are intrinsically competent and versatile enough to fulfill the varying requirements for establishing and sustaining digital enterprises Enterprise Digital Transformation Technology Tools and Use Cases features chapters on the evolving aspects of digital transformation and intelligence It covers the unique competencies of digitally transformed enterprises IIoT use cases and applications It explains promising technological solutions widely associated with digital innovation and disruption The book focuses on setting up and sustaining smart factories that are fulfilling the Industry 4.0 vision that is realized through the IIoT and allied technologies

### **Closed-Loop Systems for Next-Generation**

**Neuroprostheses** Timothée Levi, Paolo Bonifazi, Paolo Massobrio, Michela Chiappalone, 2018-04-26 Millions of people worldwide are affected by neurological disorders which disrupt the connections within the brain and between brain and body causing impairments of primary functions and paralysis Such a number is likely to increase in the next years and current assistive technology is yet limited A possible response to such disabilities offered by the neuroscience community is given by Brain Machine Interfaces BMIs and neuroprostheses The latter field of research is highly multidisciplinary since it involves very different and disperse scientific communities making it fundamental to create connections and to join research efforts Indeed the design and development of neuroprosthetic devices span involve different research topics such as interfacing of neural systems at different levels of architectural complexity from in vitro neuronal ensembles to human brain bio artificial interfaces for stimulation e.g. micro stimulation DBS Deep Brain Stimulation and recording e.g. EMG Electromyography EEG Electroencephalography LFP Local Field Potential innovative signal processing tools for coding and decoding of neural activity biomimetic artificial Spiking Neural Networks SNN and neural network modeling In order to develop functional communication with the nervous system and to create a new generation of neuroprostheses the study of closed loop systems is mandatory It has been widely recognized that closed loop neuroprosthetic systems achieve more favorable outcomes for users than equivalent open loop devices Improvements in task performance usability and embodiment have all been reported in systems utilizing some form of feedback The bi-directional communication between living neurons and artificial devices is the main final goal of those studies However closed loop systems are still uncommon in the literature mostly due to requirement of multidisciplinary effort Therefore through eBook on closed loop systems for next generation neuroprostheses we encourage an active discussion among neurobiologists electrophysiologists bioengineers computational neuroscientists and neuromorphic engineers This eBook aims to facilitate this process by ordering the 25 contributions of this research in which we highlighted in three different parts A Optimization of different blocks composing the closed loop system B Systems for neuromodulation based on DBS EMG and SNN and C Closed loop BMIs for rehabilitation

On Modeling the Spatiotemporal Processing Characteristics of the Retina Matthias Wulf, 2002

**Proceedings of the 1993 American Control Conference**, 1993

Intelligent Components for Autonomous and Semi-Autonomous Vehicles P. Bidan, S.

Boverie,1996-09-11 The IFAC Workshop on Intelligent Components for Autonomous and Semi Autonomous Vehicles ICASAV 95 was held in Toulouse France 25 26 October 1995 and provided academic and industrial researchers from all over the world with an opportunity to discuss their experiences and research results in this field Areas covered included vehicle dynamics navigation localization estimation driver assistance and energy management **Neuroscience, computing, performance, and benchmarks: Why it matters to neuroscience how fast we can compute** Felix Schürmann,Omar Awile,James Courtney Knight,Thomas Nowotny,James B. Aimone,Markus Diesmann,2023-04-26 Smart Structures and Materials ,1996 *Neural Computation in Embodied Closed-Loop Systems for the Generation of Complex Behavior: From Biology to Technology* Poramate Manoonpong,Christian Tetzlaff,2018-10-11 How can neural and morphological computations be effectively combined and realized in embodied closed loop systems e g robots such that they can become more like living creatures in their level of performance Understanding this will lead to new technologies and a variety of applications To tackle this research question here we bring together experts from different fields including Biology Computational Neuroscience Robotics and Artificial Intelligence to share their recent findings and ideas and to update our research community This eBook collects 17 cutting edge research articles covering neural and morphological computations as well as the transfer of results to real world applications like prosthesis and orthosis control and neuromorphic hardware implementation **1991 IEEE International Symposium on Circuits and Systems** ,1991 *Proceedings of the IEEE International Conference on Industrial Technology (ICIT ...)* .,2004 *Bulletin of the Polish Academy of Sciences* ,1983 *Industrial and Manufacturing Systems* Cornelius T. Leondes,1997-11-20 *Industrial and Manufacturing Systems* serves as an in depth guide to major applications in this focal area of interest to the engineering community This volume emphasizes the neural network structures used to achieve practical and effective systems and provides numerous examples *Industrial and Manufacturing Systems* is a unique and comprehensive reference to diverse application methodologies and implementations by means of neural network systems It will be of use to practitioners researchers and students in industrial manufacturing electrical and mechanical engineering as well as in computer science and engineering Quality control techniques Active noise and vibration control Chemical processing systems Process monitoring and diagnosis Robotic assembly in electronics manufacturing systems Smart structural systems of improved effectiveness Closed loop feedback control in uncertain nonlinear manufacturing systems Adaptive neural controllers in industrial systems Machine tool control systems Emphasis is placed on neural network structures for achieving practical and effective systems with numerous examples illustrating the text Practitioners researchers and students in industrial manufacturing electrical and mechanical engineering as well as in computer science and engineering will find this volume a unique and comprehensive reference to diverse application methodologies and implementations by means of neural network systems EUROMICRO '90 Workshop on Real-Time Euromicro,1990 Volume 2 is a new book It emphasizes error tolerant arithmetic online arithmetic VLSI

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