Towards a Brain-inspired Information Processing System: Modelling and Analysis of Synaptic Dynamics

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Abstract

Biological neural systems (BNS) in general and the central nervous system (CNS) specifically exhibit a strikingly efficient computational power along with an extreme flexible and adaptive basis for acquiring and integrating new knowledge. Acquiring more insights into the actual mechanisms of information processing within the BNS and their computational capabilities is a core objective of modern computer science, computational sciences and neuroscience. Among the main reasons of this tendency to understand the brain is to help in improving the quality of life of people suffer from loss (either partial or complete) of brain or spinal cord functions. Brain-computer-interfaces (BCI), neural prostheses and other similar approaches are potential solutions either to help these patients through therapy or to push the progress in rehabilitation. There is however a significant lack of knowledge regarding the basic information processing within the CNS. Without a better understanding of the fundamental operations or sequences leading to cognitive abilities, applications like BCI or neural prostheses will keep struggling to find a proper and systematic way to help patients in this regard. In order to have more insights into these basic information processing methods, this thesis presents an approach that makes a formal distinction between the essence of being intelligent (as for the brain) and the classical class of artificial intelligence, e.g. with expert systems. This approach investigates the underlying mechanisms allowing the CNS to be capable of performing a massive amount of computational tasks with a sustainable efficiency and flexibility. This is the essence of being intelligent, i.e. being able to learn, adapt and to invent. The approach used in the thesis at hands is based on the hypothesis that the brain or specifically a biological neural circuitry in the CNS is a dynamic system (network) that features emergent capabilities. These capabilities can be imported into spiking neural networks (SNN) by emulating the dynamic neural system. Emulating the dynamic system requires simulating both the inner workings of the system and the framework of performing the information processing tasks. Thus, this work comprises two main parts. The first part is concerned with introducing a proper and a novel dynamic synaptic model as a vital constitute of the inner workings of the dynamic neural system. This model represents a balanced integration between the needed biophysical details and being computationally inexpensive. Being a biophysical model is important to allow for the abilities of the target dynamic system to be inherited, and being simple is needed to allow for further implementation in large scale simulations and for hardware implementation in the future. Besides, the energy related aspects of synaptic dynamics are studied and linked to the behaviour of the networks seeking for stable states of activities. The second part of the thesis is consequently concerned with importing the processing framework of the dynamic system into the environment of SNN. This part of the study investigates the well established concept of binding by synchrony to solve the information binding problem and to proposes the concept of synchrony states within SNN. The concepts of computing with states are extended to investigate a computational model that is based on the finite-state machines and reservoir computing. Biological plausible validations of the introduced model and frameworks are performed. Results and discussions of these validations indicate that this study presents a significant advance on the way of empowering the knowledge about the mechanisms underpinning the computational power of CNS. Furthermore it shows a roadmap on how to adopt the biological computational capabilities in computation science in general and in biologically-inspired spiking neural networks in specific. Large scale simulations and the development of neuromorphic hardware are work-in-progress and future work. Among the applications of the introduced work are neural prostheses and bionic automation systems.