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Integrated neural and robotic simulations. Simulation of cerebellar neurobiological substrate for an object-oriented dynamic model abstraction process

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HIGHLIGHTS

- We integrated EDLUT neural simulator within a simulated robotic environment.
- As an embodiment example, we implemented a cerebelar-like structure controlling a simulated arm.
- The neural robotic simulator combines signals in analog/spike domains.
- Neural simulator, interface, and robotic platform operate conjointly in real time.

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ABSTRACT

Experimental studies of the Central Nervous System (CNS) at multiple organization levels aim at understanding how information is represented and processed by the brain's neurobiological substrate. The information processed within different neural subsystems is *neurocomputed* using distributed and dynamic patterns of neural activity. These emerging patterns can be hardly understood by merely taking into account individual cell activities. Studying how these patterns are elicited in the CNS under specific behavioral tasks has become a groundbreaking research topic in system neuroscience. This methodology of synthetic behavioral experimentation is also motivated by the concept of embodied neuroscience, according to which the primary goal of the CNS is to solve/facilitate the body–environment interaction.

With the aim to bridge the gap between system neuroscience and biological control, this paper presents how the CNS neural structures can be connected/integrated within a body agent; in particular, an efficient neural simulator based on EDLUT (Ros et al., 2006) has been integrated within a simulated robotic environment to facilitate the implementation of object manipulating closed loop experiments (action–perception loop). This kind of experiment allows the study of the neural abstraction process of dynamic models that occurs within our neural structures when manipulating objects.

The neural simulator, communication interfaces, and a robot platform have been efficiently integrated enabling real time simulations. The cerebellum is thought to play a crucial role in human-body interaction with a primary function related to motor control which makes it the perfect candidate to start building an embodied nervous system as illustrated in the simulations performed in this work.

1. Introduction

Computational models of various brain regions have been developed and studied for more than thirty years in order to analyze central brain functions. Computational neuroscience (CN) is the natural complement of experimental brain research, since it focuses on specific mechanisms and models which are only partially observed in anatomical or physiological studies. In particular, the cerebro-cerebellar loop has been extensively modeled since Marr

Abbreviations: CNS, Central Nervous System; PF, parallel fiber; MF, mossy fiber; CF, climbing fiber; GC, granule cell; GoC, Golgi cell; PC, Purkinje cell; DCN, deep cerebellar nuclei; IO, inferior olive; MAE, mean average error.

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and Albus [1,2], providing elegant explanations on how the forward controller operation of the cerebro-cerebellar loop seems to work. Nevertheless, these computational theories tend to focus on one part of the cerebellar circuitry and then, to extrapolate the obtained conclusions to the whole cerebro-cerebellar system. Simulating nervous systems "connected" to a body (agent or robot with sensors and actuators) is of interest for studying how certain capabilities of the nervous system (e.g. the role of the cerebellum in coordinated movements and object manipulation) are based on cellular characteristics, nervous system topology, or local synaptic adaptation mechanisms. This represents an integrative approach which aims to build the bridge between task specific experimentation (equivalent to "awake animal testing") and system neuroscience models.

This integrative approach allows us to study the role of certain nervous systems within "behavioral tasks" [3]. For this purpose, it is crucial to study nervous system models within the framework of their interaction with a body (sensors and actuators) and the environment.

This paper describes an integrated approach to the cerebellar circuit modeling within real time "behavioral tasks". The paper describes briefly: (a) a cerebellar model based on point neurons capable of being simulated in real-time. The model maintains biological interconnectivity ratios in functional medium-scale networks (rather than an ad-hoc neural network particularly designed for a specific behavioral task) that are embedded in biologically plausible control loops. (b) Testing the role of plasticity at parallel fibers-Purkinje cells. (c) Embedding the neural system model into a cerebro-cerebellar control loop connected to a Light Weight Robot (LWR) performing repetitive fast manipulations along benchmark trajectories. In order to address these three aims, we have integrated a neural simulator based on EDLUT [4] with a simulated robotic environment to facilitate the implementation of object-manipulating closed-loop experiments (action–perception closed loops).

These experiments allow us to study the neural abstraction process of dynamic models (of objects being manipulated) that occurs within our neural structures in fast manipulation tasks [5–7]. The neural simulator, the communication interface, and the simulated robotic platform have been developed and integrated taking into account computational efficiency as a major requirement in order to enable real time simulations. This platform allows us to study different neural representation and processing schemes in a specific task within a brain–body interaction framework.

1.1. Functional cerebellar models; a brief overview

Among Embodied System Neuroscience models, the well-organized structure of the cerebellum has received special attention from researchers belonging to very different fields. On one hand, neurophysiologists have studied and proposed detailed models and descriptions according to experimentally recorded cells and synaptic properties. However, it is not yet clear how specific properties of these current detailed models facilitate specific tasks at a behavioral level. On the other hand, engineers have proposed artificial approaches (only related with biology at a very high level) for biologically relevant tasks such as accurate and coordinated movements. Based on these opposed approaches, several cerebellar modeling frameworks have been proposed:

In *state-generator models*, the granule cell layer presents on/off type "granule" entities that provide a sparse coding of the state space (Marr–Albus Model [1,2], CMAC [8–10] model, or Yamazaki and Tanaka model [11–14]). These models succeed in explaining some traditional cerebellum-involving tasks such as eyelid conditioning [15] or motor control tasks [6,7,16]. In *functional models*, only the functional abstraction of specific cerebellar operations is considered: MPFIM model [17], Adaptive Filter model [18–22], APG model [23], or LWPR model [24,25]. Although in some cases, these models are also used to explain how the cerebellum works, these can be seen as problem solving approaches (that use internal structures not constrained to biologically plausible features). These functional models are also used to study the potential role of the cerebellum in tasks such as eyelid conditioning, the vestibule ocular reflex (VOR), or movement correction [24,25]. Finally, *cellular-level models* capture the biophysical features of the cerebellar neuronal topology and processing, and can be evaluated in the framework of neurophysiological experiments. These models aim to be as biologically plausible as possible. But due to their inherent complexity, their application in the context of large-scale cerebellar modeling and computation remains limited. The very first approximations in this field were developed based on the simplified models of Schweighofer–Arbib [26,27].

1.2. How to embody the cerebellar circuitry

The cerebellar network has been at the core of neurocomputational theories since the 1960s, when Eccles proposed the Beam Theory [28] and Marr and Albus, the Motor Learning Theory [1,2]. Later on, Ito developed the forward controller theory [4,29–32]. Since then, the view has been crystallized on two main concepts that can be synthesized as follows; the way the cerebellum operates is by decorrelating the inputs in the granular layer and detecting known patterns in Purkinje cells. Pattern recognition is regulated by memory storage at the parallel-fiber-Purkinje-cell synapse. When unfamiliar patterns are detected repeatedly, the Purkinje cells change their firing rate and regulate activity in the deep cerebellar nuclei (DCN), thereby emitting the corrective terms used for highly accurate motions (skillful control performance).

Despite its attractiveness and simplicity, this theory only partially accounts for the capabilities of the cerebellum. Furthermore, recent experimental data indicate that the cerebellar system is much more complex than initially stated. Just to make a very short survey, the mechanisms of the granular layer go far beyond simple decorrelation [33], long-term synaptic plasticity does not occur only at the parallel fibers (PF) [33–35], the inferior olive (IO) operates as a complex timing system and not simply to drive Purkinje cell plasticity [36], the Purkinje cells and the DCN cells have operative states that go far beyond the concept of firing rate regulation [37]. The core idea is that our knowledge on the functioning of neuronal networks of the cerebellum is still rather vague, and that we have to develop new computational tools to investigate cerebellar network dynamics beyond the current existing paradigms.

The available neurophysiological data (which is essential for understanding the functional organization of the cerebellum and related structures) has to be analyzed to investigate the particular processing capabilities of each neuron and of its internal dynamics. Emphasis must be put on proving how the network processing capabilities are supported by the low-level characteristics of each neuron type. Many of the specific cerebellar neural types have already been implemented in Python–NEURON–EDLUT software simulators [38,39] and there are even specific repositories gathering different kinds of models [40,41].

1.3. Modeling the cerebellar circuits

When modeling the cerebellar circuit with a bottom-up approach, the cerebellar network needs to be modeled aiming at the construction and generation of a complete cerebellar functional network, tested in realistic functional conditions and endowed with plasticity rules. This process demands the comprehension of