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Distributed and Modular Bio-Inspired Architecture for Adaptive Motor Learning and Control

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Recent studies have demonstrated that autonomous robots can outperform the task they are programmed for, but are limited in their ability to adapt to unexpected situations (Ingrand and Ghallab, 2017). This limitation is due to the lack of generalization, i.e., the robot can not transfer knowledge across multiple situations. Even the application of modern artificial intelligence (AI) techniques does not support a robust generalization when the range of probable inputs is infinite (Yang et al., 2018; Mnih et al., 2015; Cai et al., 2017; Kober et al., 2013). As a matter of fact, AI methods can interpolate knowledge but not extrapolate it, i.e., they can adapt on new, unseen data that are within the bounds of their experience, but not on data that are outside the bounds. So far, robots have been mostly treated as stand-alone systems in a vacuum, while the real world is more complex and includes continuous interaction with external entities. Accordingly, the design of a generalized robotic controller is not trivial, in particular when the dynamical condition are unknown.

From the observation of nature, it is possible to deduct the level of competence that animals have when interacting with the environment. The study and understanding of the central nervous system (CNS), which is the main responsible of the body complex movements during the interaction with the environment (Wolpert and Ghahramani, 2000; D'Angelo and Wheeler-Kingshott, 2017), may give new insights about the artificial replication of the animals' interactive and adaptive behaviour. As a matter of fact, the CNS is constituted by different regions which role, relation and distribution are important for the optimal execution of complex tasks (see (Caligiore et al., 2017) for a review).

This investigation has its foundation in the Human Brain Project (Markram et al., 2011), which is trying to achieve a more clear understanding of the brain's capabilities. Here, we propose the initial design of a distributed and modular bio-inspired control architecture that aims to artificially replicate the CNS areas involved in planning and executing voluntary movements (figure 1).

The distribution of the architecture is based on the "divide and conquer" concept, where the whole system is decomposed into separated and specialized components. The modularity refers to the independence of each component and its interdependence to the other structures of the architecture. The malfunctioning of each module only affects its contribution to the system and not to the operating state of the other modules. The design of the architecture is specific for gross motor skills involved in the coordination of a robotic arm during the interaction with an external system, such as dynamical target reaching and object manipulation. The control system will be tested mainly on virtual robots in the physical simulation environment offered by the Neurorobotics Platform (NRP) (Falotico et al., 2017). The NRP not only includes a variety of robot and environments, but also a detailed physics simulator. The architecture follows the guidelines from different studies (Caligiore et al., 2017; Houk and Wise, 1995; Casellato et al., 2012; Tomita and Yano, 37 2007; Ryczko et al., 2016; Santos and Matos, 2011) and includes CNS regions such as the brain stem (action regulation), the cerebellum (motor adaptation), the spinal cord (motor pattern generation), the basal ganglia (action selection), and the motor cortex(Initiation, planning, procedure of motion). The CNS areas will be modeled combining classical control and robotics methods together with bio-inspired AI techniques.

This study does not only aim to artificially mimic the connectivity and functionality of the CNS (as seen in previous studies (Floreano et al., 2014; Prescott et al., 2016; Mitchinson and Prescott, 2016)), but to also analyze, with practical evidence, how different brain regions map context-sensitive motor skills as proposed by Wolpert and Kawato (Wolpert and Kawato, 1998). This is because we believe that the modularity of each brain region is fundamental for the extrapolation of valuable information from heterogeneous dynamical stimuli. This extrapolation could facilitate the motor prediction and adaptation in changing or unknown conditions.

Among these CNS regions, it is well known the pivotal role of the cerebellum in motor learning and adaptation (Ito, 2008; Dean et al., 2010; Verduzco-Flores and O'Reilly, 2015; D'Angelo, 2014). Several robots have been already endowed with cerebellar-like control architectures with promising results (Garrido Alcazar et al., 2013; Tolu et al., 2012, 2013; Vannucci et al., 2016;

Casellato et al., 2015). However, these studies mostly focused on the functionality of a specific CNS region, keeping the contribution and dependency with other brain structures neglectable. Moreover, the experiments were run in simplified conditions with marginal dynamics, absent interaction with the environment, and relative goal, i.e., goal not related to an external reference or exteroceptive sensors.

Our investigation will firstly focus on the cerebellum. The way the cerebellum maps and processes the sensory information in relation to the execution of complex dynamical tasks is not totally clear. We assume that an answer could be found in the regular and modular structure of the cerebellum, where distinct functional units can be observed (Ruigrok, 2011). In 2006, Ito claimed that in each unit a forward or an inverse internal model is captured for representing the relation between action and outcome (Ito, 2006). In addition to Ito's internal models theory, there is also evidence that the human cerebellum can be modeled by a combination of both inverse and forward internal models (Wolpert and Kawato, 1998). Nonetheless, this mixed model has not widely been used in robotic control in particular when the characteristics of the robot and/or the environment change. The secondary aspect

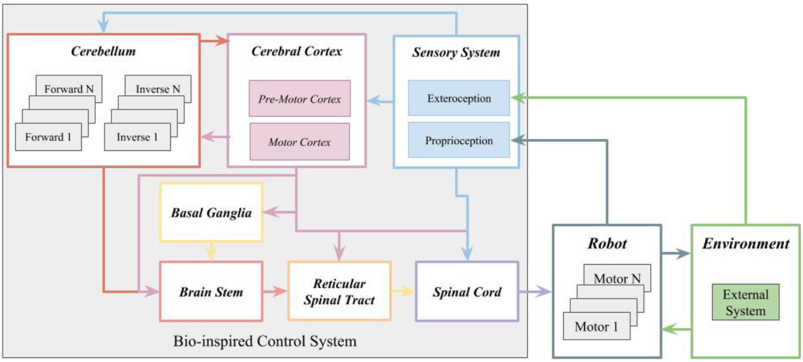

FIGURE 1: The proposed bio-inspired architecture aims to solve the problem of robotic agent (in grey) adaptation during the interaction with an external system (in green). The system is modelled to control the coordination of a robotic arm during dynamical target reaching and object manipulation. The illustration shows only the high-level connections and distribution. Each building block will contains bio-inspired structures and classic control theory algorithms. Tbe main idea, respect to the literature, is to focus on how the CNS regions internally specialize and map heterogeneous motor skills.

to be investigated is the reciprocal interaction between the cerebellum and other CNS areas (Houk and Wise, 1995). The cerebellum will be integrated in the distributed architecture shown in figure 1.

Starting from the theory that the cerebellum is decoupled into sub-units, we are going to analyze how the specialization of each unit and their cooperation influences the mapping of heterogeneous dynamical information onto motor skills. From this analysis, we expect to comprehend how the malfunctioning of a specific unit can influence the final corrective action of the cerebellum. At the same time, this could help to understand which feature is not mapped correctly inside the internal model and consequentially correct this lack. Thereafter, from a macro-level perspective, we will investigate how the learned experience is exchanged and utilized across different CNS regions for planning and executing context-related motor commands. This study could give new guidelines for modeling a more robust and distributed robotic control architecture. As matter of fact, the CNS demonstrated that the malfunctioning of one system component does not preclude the operating state of the whole architecture, which is a beneficial aspect for modern autonomous robot. On the other hand, the application of neuro-scientific assumptions on practical experiments could give a feedback and open new lines of research.

To conclude, the outcome of the present investigation will provide the state-of the-art for more complex bio-inspired control architectures for neuro-robots that learn from experiences under varying dynamical conditions.

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Keywords: cerebellum, modular, neuro-robotics, bio-inspired architecture, motor control and learning, adaptive control

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