Measuring Entropy in Embodied Neural Agents with Homeostasic Units: A Link Between Complexity and Cybernetics

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Abstract. We present a model of a recurrent neural network with homeostasic units, embodied in a minimalist articulated agent with a single link and joint. The configuration of the agent is determined by the total activation level or kinetic energy of the network. We study the complexity patterns of the neural networks, and see how the entropy of the neural controller state and agent configuration changes with the relative characteristic time of the homeostasis when compared with the excitatory-inhibitory activation dynamics of network. We also present a meta-model of embodied neural agents, that serves as conceptual framework to study self-perturbation and the self-organization in embodied neural agents. Simulation results show that homeostasis significantly influences the dynamics of the network and the controlled agent, allowing the system to escape fixed-points and produce complex aperiodic behavior. The relation between the characteristic time of homeostasis and the characteristic time of main excitatory-inhibitory activation dynamics was found to be non-linear and non-monotonic. We use these findings to connect the perspectives of classical cybernetics on homeostasis to complexity research.

1 Introduction

Motivated by concepts and ideas from autopoetic philosophy [1], ecological psychology [2], complex systems theory [3], and situated artificial intelligence research [4,5], we present a recurrent neural network model [6] with homeostasic units [7] and study its complexity patterns. Homeostasis is modeled using adaptive thresholds in units, whose effect is to (try to) push units to an equilibrium or rest activation value. The agent consists of a link and a rotational joint in a 2D plane. The agent configuration is fully determined by a single degree of freedom — the joint angle. Attached to the link is a muscle whose contraction/distension produces an angular displacement of the link. The activity of the neural units determines the level of contraction of the muscle. Homeostasis is modeled in our neural network as an adaptive threshold in neural units. We use measures of entropy to see how the characteristic time of homeostasic process affects the complexity of the dynamics of the neural controller (micro state), and the resulting configuration of the agent (the macro state).

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Our results show that even though units individually try to move to a rest/equilibrium activation value, the system as a whole never reaches equilibrium because of connections between neural units. Instead, the system exhibits complex (mostly aperiodic) patterns, generating a source of novelty/variety in agent behavior. On the other hand, if homeostasis is not used, the system tends to a stable fixed point or a small region of the state space (if noise is present). To abstract and guide our work, we begin by presenting a generic meta-model of embodied neural agents that can be used to understand in a programmatic way how self-organization and neural development relates to adaptive behavior and sensoriomotor coordination tasks (both in high-order animals and humans).

Below, we present the meta-model for embodied neural agents (section 2). Next, we describe the particular embodied neural agent model studied in this article (section 3), and present the results of several computational experiments using the model (section 4). Section 5 summarizes simulation results, relates it with other work on on homeostasis, and makes a conceptual link with classical cybernetics.

2 A Generic Meta-model for Cognitive Development and Sensoriomotor Coordination in Embodied Neural Agents

To study self-organization in embodied neural agents and the development of sensori-motor skills, we have made an abstract characterization of this type of agent model. [See [8] for another characterization of embodied developmental agents, taking the more traditional computational perspective.]

Agents are characterized at two levels: the macro-level and the micro-level. The macro-level is defined by the configuration state — a formal description of the agents body posture in space, as seen by an external observer or as made apparent to the agent through self-perception. A small number of degrees of freedom is often required to describe an agent at this level. The micro-level is a characterization of the state of its neural controller. This includes the activation level of neural units (e.g., mean firing rate), units' thresholds, and neural connections' weights. Usually, the micro-level requires a much higher number of degrees of freedom to be fully described than the macro-level, since an agent with few links and joints may have a controller with many neural units. Interfacing the micro and macro-levels, agent descriptions include the way the neural controller is connected to the agents' body — both in muscular connections (efferent) and in the way sensation-perception cells/inputs impinge on the neural controller.

Agents are often situated in some environment, in such a way that its behavior and interaction with the environment may be observed by some external observer. In fig. 1, we make a sketch representation of the relationship between the agent, its environment, the external observer, and the two levels of description.

A key aspect of natural agents, is that the mapping from the (micro) neural level and the (macro) configuration level is not one-to-one. The coordinated