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Where neuroscience and dynamic system theory meet autonomous robotics: A contracting basal ganglia model for action selection

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ABSTRACT

Action selection, the problem of choosing what to do next, is central to any autonomous agent architecture. We use here a multi-disciplinary approach at the convergence of neuroscience, dynamical system theory and autonomous robotics, in order to propose an efficient action selection mechanism based on a new model of the basal ganglia. We first describe new developments of contraction theory regarding locally projected dynamical systems. We exploit these results to design a stable computational model of the cortico-baso-thalamo-cortical loops. Based on recent anatomical data, we include usually neglected neural projections, which participate in performing accurate selection. Finally, the efficiency of this model as an autonomous robot action selection mechanism is assessed in a standard survival task. The model exhibits valuable dithering avoidance and energy-saving properties, when compared with a simple if-then-else decision rule.

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1. Introduction

Action selection is the problem of motor resource allocation an autonomous agent is faced with, when attempting to achieve its long-term objectives. These may vary from survival and reproduction to delivering letters to researchers' offices, depending on the nature of the considered agent (animal, robot, etc.). Action selection is a topic of interest in various disciplines, including ethology, artificial intelligence, psychology, neuroscience, autonomous robotics, etc. We address here the question of action selection for an autonomous robot, using a computational model of brain regions involved in action selection, namely the cortico-baso-thalamo-cortical loops. In order to avoid unwanted dynamical behaviors resulting from a highly recurrent network, we use contraction analysis (Lohmiller & Slotine, 1998) to obtain a rigorous proof of its stability. The efficiency of this action selection mechanism (ASM) is assessed using a standard minimal survival task in a robotic simulation.

The basal ganglia are a set of interconnected subcortical nuclei common to all vertebrates and involved in numerous processes, from motor functions to cognitive ones (Middleton & Strick, 1994; Mink, 1996). Their role is interpreted as a generic selection circuit, and they have been proposed to form the neural substrate of action selection (Krotopov & Etlinger, 1999; Mink, 1996; Redgrave,

Prescott, & Gurney, 1999). The basal ganglia are included in cortico-baso-thalamo-cortical loops (Fig. 1), five main loops have been identified in primates (Alexander, Crutcher, & DeLong, 1990; Alexander, DeLong, & Strick, 1986; Kimura & Graybiel, 1995): one motor, one oculomotor, two prefrontal and one limbic loop. Within each of these loops, the basal ganglia circuitry is organized in interacting channels, among which selection occurs. Depending on the considered loop, this selection may concern, for example, the target of an upcoming saccadic movement, the target of a reaching movement or the piece of information to be stored in working memory. The output nuclei of the basal ganglia are inhibitory and tonically active, and thus maintain their targets under sustained inhibition. Selection occurs *via* disinhibition (Chevalier & Deniau, 1990): the removal of the inhibition exerted by one channel on its specific target circuit allows the activation of that circuit. When considering action selection, the basal ganglia channels are thought to be associated to competing action primitives. Given sensory and motivational inputs, the basal ganglia are thus supposed to arbitrate among these actions and to allow the activation of the winner by disinhibiting the corresponding motor circuits.

The considered network contains a large number of closed loops, from the large cortico-baso-thalamo-cortical loop, to small loops formed by the interconnections between nuclei within the basal ganglia and between the thalamus and the cortex. A system with such a structure may exhibit varied dynamical behaviors, some of which should be avoided by an ASM, like reaching a standstill state which does not depend anymore on the

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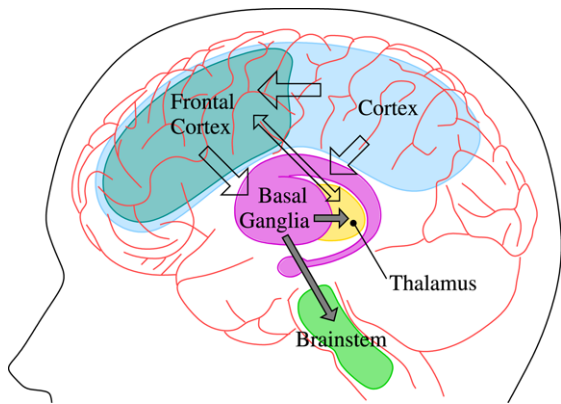


Fig. 1. Cortico-baso-thalamo-cortical loops. The basal ganglia receive inputs from the whole cortex, but establish loops with the frontal areas only. Shaded arrows: inhibitory projections.

external input. This motivates the use of a theoretical framework to study the dynamics of basal ganglia models. We propose to use contraction analysis (Lohmiller & Slotine, 1998) in order to guide the design of a new model of the basal ganglia whose stability can be formally established. Contraction analysis is a theoretical tool used to study the dynamic behavior of nonlinear systems. Contraction properties are preserved through a number of particular combinations, which is useful for a modular design of models.

Numerous computational models of the BG have been proposed in order to investigate the details of the operation of the basal ganglia disinhibition process (see Gillies & Arbruthnott, 2000; Gurney, Prescott, Wickens, & Redgrave, 2004, for recent reviews). Among these, the model proposed by Gurney, Prescott, and Redgrave (2001a, 2001b) (henceforth the GPR model) has been successfully tested as an action selection mechanism for autonomous agents (Girard, Cuzin, Guillot, Gurney, & Prescott, 2003; Girard, Filiat, Meyer, Berthoz, & Guillot, 2005; Montes-Gonzalez, Prescott, Gurney, Humphries, & Redgrave, 2000; Prescott, Montes-Gonzalez, Gurney, Humphries, & Redgrave, 2006). In particular, it was shown to be able to solve a minimal survival task, and, compared with a simpler winner-takes-all mechanism, displayed dithering avoidance and energy-saving capabilities.

We present here an action selection mechanism based on a contracting computational model of the basal ganglia (or CBG). In order to adapt the contraction theory to the analysis of rate-coding artificial neural networks, we first extend it to locally projected dynamical systems (Section 2). Using the resulting neuron model and contraction constraints on the model's parameters, we build a computational model of the basal ganglia including usually neglected neural connections (Section 3). We then check the selection properties of the disembodied model and compare them to those of the GPR, so as to emphasize the consequences of using contraction analysis (Section 4). We finally test its efficiency in a survival task similar to the one used to evaluate the GPR (Girard et al., 2003), and emphasize its dithering avoidance and energy-saving properties by comparing it to a simple if-then-else decision rule (Section 5).

Preliminary versions of the basal ganglia computational model were presented in Girard, Tabareau, Berthoz, and Slotine (2006) and Girard, Tabareau, Slotine, and Berthoz (2005).

2. Nonlinear contraction analysis for rate-coding neural networks

Basically, a nonlinear time-varying dynamic system is said to be *contracting* if initial conditions or temporary disturbances are

forgotten exponentially fast, that is, if any perturbed trajectory returns to its nominal behavior with an exponential convergence rate. Contraction is an extension of the well-known *stability* analysis for linear systems. It has the desirable feature of being preserved through hierarchical and particular feedback combinations. Thus, as we will see below, contraction analysis is an appropriate tool to study stability properties of rate-coding neural networks.

In addition, when a system is contracting, it is sufficient to find a particular bounded trajectory to be sure that the system will eventually tend to this trajectory. Thus contraction theory is a convenient way to analyze the dynamic behavior of a system without linearized approximations.

2.1. Contraction theory

We summarize the differential formulation of contraction analysis presented in Lohmiller and Slotine (1998). Contraction analysis is a way to prove the exponential stability of a nonlinear system by studying the properties of its Jacobian. Consider an n -dimensional time-varying system of the form:

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), t) \quad (1)$$

where $\mathbf{x} \in \mathbb{R}^n$ and $t \in \mathbb{R}_+$ and \mathbf{f} is a $n \times 1$ nonlinear vector function which is assumed in the remainder of this paper to be real and smooth, in the sense that all required derivatives exist and are continuous. This equation may also represent the closed-loop dynamics of a neural network model of a brain structure. We recall below the main result of contraction analysis (see Lohmiller and Slotine (1998), for a proof and more details).

Theorem 1. Consider the continuous-time system (1). If there exists a uniformly positive definite metric

$$\mathbf{M}(\mathbf{x}, t) = \Theta(\mathbf{x}, t)^T \Theta(\mathbf{x}, t)$$

such that the generalized Jacobian

$$\mathbf{F} = (\dot{\Theta} + \Theta \mathbf{J}) \Theta^{-1}$$

is uniformly negative definite, then all system trajectories converge exponentially to a single trajectory with convergence rate $|\lambda_{\max}|$, where λ_{\max} is the largest eigenvalue of the symmetric part of \mathbf{F} .

The symmetric part of a matrix \mathbf{A} is $\mathbf{A}_s = 1/2(\mathbf{A} + \mathbf{A}^T)$. A matrix $\mathbf{A}(\mathbf{x}, t)$ is uniformly positive definite if there exists $\beta > 0$ such that $\forall \mathbf{x}, t \quad \lambda_{\min}(\mathbf{A}(\mathbf{x}, t)) \geq \beta$.

2.2. Neural networks and locally projected dynamical systems

Networks of leaky integrators are widely used to model the behavior of neuronal assemblies (Dayan & Abbott, 2001). A leaky-integrator network is usually described by the following set of equations

$$\tau_i \dot{x}_i = -x_i(t) + \sum_{j \neq i} K_{ji} x_j(t) + I(t)$$

where $x(t)$ is the synaptic current of a neuron, τ_i its time constant, K_{ji} the synaptic projection weight from neuron j to neuron i and $I(t)$ the input coming from an external source. Next, $x(t)$ is converted into a non-negative firing rate $y(t)$ using a transfer function, for instance

$$y(t) = \max(x(t), 0) = [x(t)]_+$$

Another way to enforce non-negativity of the firing rate is to use through *locally projected dynamical systems* (IPDS in short). These systems were introduced in Dupuis and Nagurney (1993)

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