

Towards Modular Neuromimetic Robot Controllers

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Abstract—The central nervous system of mammals is composed of various modules accumulated in the course of evolution. New functionalities have been progressively added, increasing adaptivity and interacting with previous ones in a cooperative manner. In vision, for instance, the long-studied saccadic circuitry implies circuits in the reticular formation, the superior colliculus, the cerebellum, the basal ganglia, and the cortex.

How does the brain achieve satisfactory global behaviors, while being composed of such a large collection of interacting nonlinear dynamic systems? One suggested hypothesis is that these functional modules verify a nonlinear stability-like property called contraction, which is automatically preserved in most system combinations. Such property may also guide robust, recursive designs of robot sensing and control architectures.

The purpose of the program introduced in this paper is to test this hypothesis, and specifically to evaluate the possibility of building a contracting neuromimetic model of the entire saccadic circuitry, from cortex frontal eye fields down to the reticular formation burst generators. We present here our first results, concerning the brainstem circuitry, the cortex-basal ganglia circuitry, and their preliminary robotic implementations.

I. INTRODUCTION

Although neurons as computational elements are 7 orders of magnitude slower than their artificial counterparts, the primate brain grossly outperforms robotic algorithms in all but the most structured tasks. Parallelism alone is a poor explanation, and much recent functional modelling of the central nervous system focuses on its modular, heavily feedback-based computational architecture, the result of accumulation of subsystems throughout evolution. As specific instances, motion control architecture in vertebrates involves combinations of simple motor primitives [1], [2]; human emotional response involves both fast archaic loops bypassing the cortex, and slower cortical loops [3], [4]; in human vision, the saccadic circuitry involves circuits in the reticular formation, the superior colliculus, the cerebellum, the basal ganglia, and the cortex.

Modularity has also been a recurrent theme in cybernetics and AI history [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

However, in themselves, accumulations and combinations of stable elements have no reason to be stable — passivity analysis [16], for instance, is motivated by such concerns [17]. Hence the hypothesis in [18] that evolution will favor

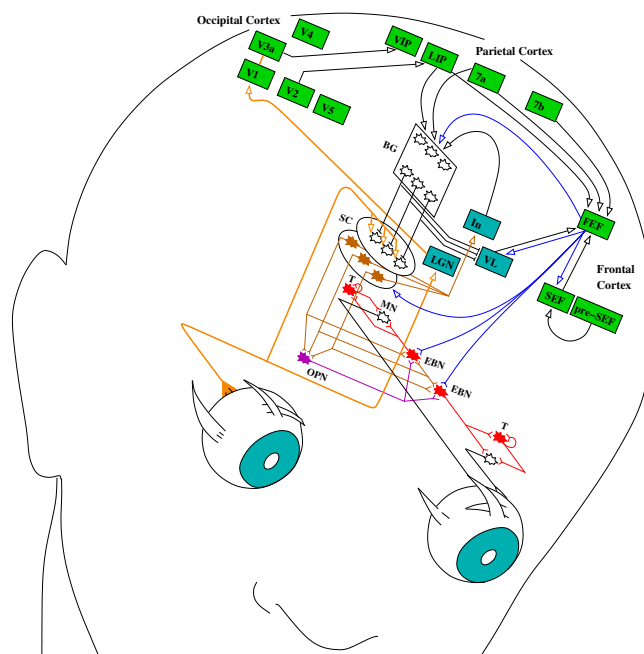


Fig. 1. Saccadic circuitry. BG: basal ganglia; EBN: excitatory burst neurons; FEF: Frontal Eye Fields; In: intralaminar thalamic nucleus; LGN: lateral geniculate nucleus; LIP: Lateral intra-parietal area; MN: motoneurons; OPN: omnipause neurons; SC: superior colliculus; SEF: Supplementary Eye Fields; T: tonic neurons; VIP: Visual intra-parietal area; VL: ventro-lateral thalamus. Adapted with permission from [5]

a particular form of state stability, which automatically guarantees stability in combinations, such as parallel, series, feedback, or multiresolution. Such a form of nonlinear stability, called "contraction" [19], can be characterized mathematically.

The goal of the research program introduced in this paper is to test this hypothesis, and specifically to evaluate the possibility of building a contracting neuromimetic model of the entire saccadic circuitry, from cortex frontal eye fields down to the reticular formation burst generators. We present here our first results concerning the brainstem circuitry, the cortex-basal ganglia circuitry, and their preliminary robotic implementations.

Contraction analysis on the one hand, and the neu-

romimetic approach to robotics (or neurobotics) on the other hand, have already been shown to be valuable when designing robotic systems. We argue that taking inspiration from the brain modularity and using contraction theory accordingly as a design tool will allow the design of more robust and efficient robotic architectures.

II. BRAIN MODULAR ARCHITECTURE: THE SACCADIC CIRCUITRY

The mammal brain is made of a number of distinct regions (cortex, basal ganglia, cerebellum, brainstem, etc.), some of which are phylogenetically recent, while some others are inherited from much more ancient species. This is especially striking in a number of well-studied subsystems, like the rat defense system [20], the action selection mechanisms [21] or the saccadic circuitry [22], [23], [24], [25], [26].

The saccadic circuitry can be divided in two broad pathways (fig. 1). In the short and ancient one, visual information gathered from the retina is directly projected to retinotopic neuronal maps in the superficial layers of the superior colliculus (SC), saccade targets are selected in deeper SC layers (probably in interaction with the basal ganglia (BG) in BG-SC loops) and motor commands are generated accordingly in the reticular formation saccade burst generator (or SBG, containing the EBN, T, OPN and MN neurons represented in fig. 1), under an adaptive supervision of the cerebellum. This circuit, also present in goldfish [27], allows short latency saccades without any intervention of the cortex. In the longer pathway, visual information is conveyed through the thalamus to the cortical occipital, parietal and then frontal areas, before reaching the basal ganglia and the colliculus. This pathway allows the generation of more cognitive behaviors, including inhibition of saccades, working memory, sequence learning and selection modulated by attention and motivation [28].

This brain circuitry, which has been one of the most studied in neuroscience in the last 30 years, thus appears to be made of multiple intricate loops. Numerous computational models of individual saccadic modules have been proposed, but a few of them only considered the operation of the whole circuitry (refer to [29] for a review). We thus propose to address this problem of global operation and module interactions, using the contraction analysis as a tool, guiding the model design.

III. CONTRACTION ANALYSIS AND COMBINATIONS

A nonlinear time-varying dynamic system is called *contracting* if initial conditions or temporary disturbances are forgotten exponentially fast. Thus, finding a particular trajectory of a contracting system is sufficient to be sure that it will eventually tend to this trajectory. Of course, the particular trajectory can be driven by sensory inputs and thus have a non-trivial shape.

Theorem 1: Consider a n -dimensional time-varying system of the form:

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

where $\mathbf{x} \in \mathbb{R}^n$ and $t \in \mathbb{R}_+$ and \mathbf{f} is $n \times 1$ non-linear vector function which is assumed to be real and smooth.

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 the all system trajectories converge exponentially to a single trajectory with convergence rate $|\tau_{max}|$, where τ_{max} is the largest eigenvalue of the symmetric part of \mathbf{F} . The system is said to be *contracting*.

It can be shown conversely that the existence of a uniformly positive definite metric with respect to which the system is contracting is also a necessary condition for global exponential convergences of trajectories. In the linear time-invariant case, a system is globally contracting if and only if it is strictly stable, with \mathbf{F} simply being a normal Jordan form of the system and \mathbf{Q} the coordinate transformation to that form.

This approach via the analysis of the Jacobian is well adapted to study the dynamics of artificial neural networks made of nonlinear components. Moreover, contraction has the advantage of being preserved through basic system combinations (hierarchies, negative feedback, etc., see below), it is thus possible study the contraction of isolated modules and then to obtain the contraction of a large system made of these modules. We present here the two mean combination results for the study of neuromimetic robot controllers.

Hierarchical combination. Consider two contracting systems, of possibly different dimensions and metrics (say \mathbf{M}_1 and \mathbf{M}_2) and connect them in series, leading to a smooth virtual dynamics of the form:

$$\begin{pmatrix} \delta \mathbf{z}_1 \\ \delta \mathbf{z}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{F}_1 & 0 \\ \mathbf{G} & \mathbf{F}_2 \end{pmatrix} \begin{pmatrix} \delta \mathbf{z}_1 \\ \delta \mathbf{z}_2 \end{pmatrix}$$

where $\delta \mathbf{z}_1$ (resp. $\delta \mathbf{z}_2$) is the virtual displacement induced by the metric \mathbf{M}_1 (resp. \mathbf{M}_2). Then the overall system is contracting, as long as \mathbf{G} is bounded. By recursion, the result extends to hierarchies or cascades of contracting systems of arbitrary depths.

Negative feedback. We present here a particular feedback connection which automatically gives rise to contraction of the whole system. This kind of connection is very important in neuroscience because it implies inhibitory loops which are believed to be crucial in functional behavior [23].

Consider two contracting systems, of possibly different dimensions and metrics, and connect them in feedback, in such a way that the overall virtual dynamics is of the form

$$\frac{d}{dt} \begin{pmatrix} \delta \mathbf{z}_1 \\ \delta \mathbf{z}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{F}_1 & -\mathbf{G}(\mathbf{z}, t) \mathbf{B} \\ \mathbf{G}(\mathbf{z}, t)^T \mathbf{A}^T & \mathbf{F}_2 \end{pmatrix} \begin{pmatrix} \delta \mathbf{z}_1 \\ \delta \mathbf{z}_2 \end{pmatrix}$$

with \mathbf{A}, \mathbf{B} two square matrices. The overall system is contracting if

1) \mathbf{A} and \mathbf{B} are symmetric positive definite, and

2) there exists $\beta > 0$ such that

$$\dot{\mathbf{A}} + \mathbf{A} \cdot \mathbf{F}_1 + \mathbf{F}_1^T \mathbf{A} \leq -\beta \mathbf{A}$$

$$\dot{\mathbf{B}} + \mathbf{B} \cdot \mathbf{F}_2 + \mathbf{F}_2^T \mathbf{B} \leq -\beta \mathbf{B}$$

We mention a last property which does not deal with combination but appear to be essential when dealing with neurons. Indeed, many continuous model of neurons (Hodgkin-Huxley, integrate-and-fire, FitzHugh-Nagumo, ...) combine a linear differential equation (sometimes multidimensional) which describes the dynamic of the neuron, with a so-called “transfer function” which induces a non-linear behaviour. These transfer functions are simply a way to maintain the system in a convex region. The leaky-integrator rate neuron model we use as a building brick of our models is a typical example of this (τ : time constant in ms , I : input in mV):

$$\tau \frac{da}{dt} = I - a \text{ and } y = [a]^+$$

where the transfer function $[]^+$ satisfies $[I]^+ = 0$ if $I < 0$ and $[I]^+ = I$ otherwise.

The property below enables to study the contraction of that kind of system by just analysing its linear part.

Contraction analysis on convex regions. Consider a contracting system $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t)$ maintained in a convex region Ω (i.e. a region Ω in which any shortest connecting line (geodesic) $\int_{\mathbf{x}_1}^{\mathbf{x}_2} \|\delta \mathbf{x}\|$ between two arbitrary points \mathbf{x}_1 and \mathbf{x}_2 in Ω is completely contained in Ω). Then all trajectories in Ω converge exponentially to a single trajectory. Furthermore, the contraction rate can only be sped up by the convex constraint.

These contraction properties are systematically exploited in the study of the saccadic circuitry models we describe below.

IV. CONTRACTING MODEL OF THE SUPERIOR COLLICULUS AND SACCADIC BURST GENERATOR

The superior colliculus is a layered structure located on the dorsal surface of the brainstem. The superficial layers of the right (resp. left) superior colliculus receive visual information from the retina and from the visual areas of the cortex, concerning the left (resp. right) visual hemifield. These layers are retinotopic: the coordinates of targets are coded by topographically organized populations of active neurons using a complex logarithmic mapping (upper part of fig. 2). Intermediate layers of the SC are also retinotopic and are in register with the mapping of the upper layers. They have a motor activity, as population activity is recorded only when a saccade is generated, and project to the reticular formation SBGs. This topographic code is thus transformed into the rate code used in the segregated upward, downward, leftward and rightward SBG (lower part of fig. 2), by the so-called *spatio-temporal transformation*.

We developed a neuromimetic model of the SC and SBG avoiding the inherently non-contracting architecture of numerous previous models. In these models, strong short-range recurrent excitations in the SC maps lead to an exponential growth of neural activity up to its upper boundary, and thus to an infinitely sustained memory, in total contradiction with the exponentially-fast forgetting of initial conditions implied by contraction.

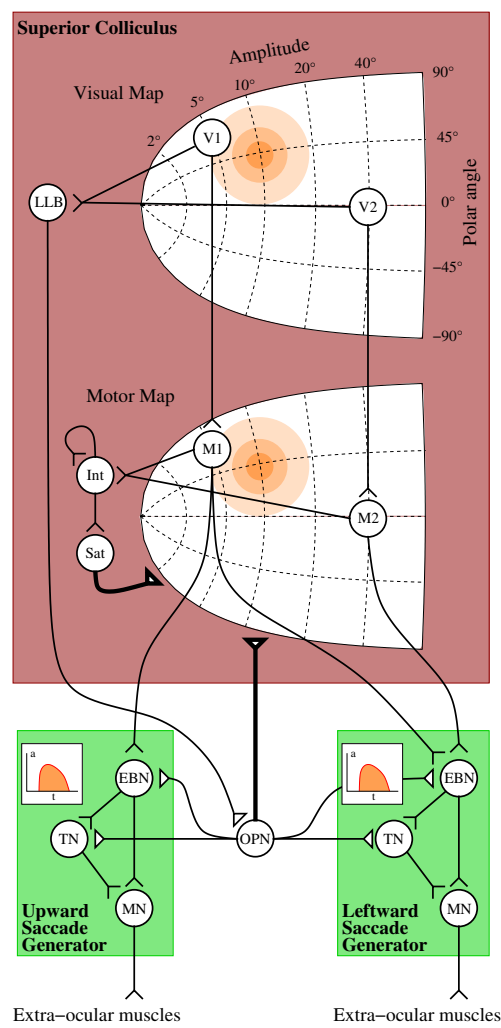


Fig. 2. Superior Colliculus Model Architecture. For simplicity, only one colliculus and two SBG (upward and leftward), without the crossed inhibitory projections, are represented. Two neurons are represented in each collicular map (V1, V2 and M1, M2, for visual and motor maps resp.). Shaded circles in collicular maps represent the gaussian activity generated by a $(10^\circ, 10^\circ)$ target, while insets in the saccadic generators represent the temporal code in the EBNs generated to drive the muscles. Open triangles represent excitatory synapses; triangles represent inhibitory synapses; bold connections affect the whole map. Int, Sat: summation and saturation mechanism, LLB: long-lead burst neurons, EBN, TN, MN, OPN as in fig. 1.

We based our model on mathematical considerations concerning the geometry of the collicular maps and the spatio-temporal transformation [30], which led us to rediscover the summation-saturation transformation mechanism of [31]. In this mechanism, the SC sends to each SBG a weighted sum of the activity of the motor layer, where the weights are chosen so that this sum is proportional to the amplitude of the saccade on the SBG axis. Simultaneously, another neuron with a time constant much larger than the duration of the saccadic burst integrates the unweighted sum of the SC motor activity and strongly inhibits the motor layer when a given threshold is reached (the values of the parameters are given in table I):

$$I_{Mot}(X, Y) = y_{Vis}(X, Y) - w_{OPN}^{Mot} y_{OPN} - w_{Sat}^{Mot} y_{Sat}$$

$$I_{Int}(X, Y) = w_{Mot}^{Int} \sum_{X, Y} y_{Mot}(X, Y)$$

$$I_{Sat}(X, Y) = y_{Int}(X, Y) - \epsilon_{stop}$$

For the SBG part of the model, we used the simplest hierarchical mechanism allowing the transformation of the burst coming from the SC into the specific burst-tonic activity of ocular motoneurons. Long-lead burst neurons (LLB) are in charge of triggering saccades by inhibiting the OPN, when the activity on Vis reaches the ϵ_{trig} threshold:

$$I_{LLB} = w_{Vis}^{LLB} \sum_{X, Y} (y_{Vis}(X, Y)) - \epsilon_{trig}$$

$$I_{OPN} = -y_{LLB} + \epsilon_{OPN}$$

The four SBG circuits are identical, all of them are gated by OPN activity, and those operating in opposite directions are coordinated by the IBN crossed projections. The EBN and IBN activity is identical and defined by:

$$I_{BN}^D = \sum_{X, Y} (w_{Mot}^{BND} y_{Mot}(X, Y)) - w_{OPN}^{BN} y_{OPN}$$

with $D \in \{U, D, L, R\}$. The EBN and IBN activity is integrated by motor (MN) and tonic neurons (TN) and then transmitted to the six eye's muscles.

$$I_{TN}^D = w_{BN}^{TN} (y_{EBN}^D - y_{IBN}^{Dop})$$

$$I_{MN}^D = w_{BN}^{MN} (y_{EBN}^D - y_{IBN}^{Dop}) + y_{TN}$$

where D^{op} is the opposite direction of D .

The preliminary constraint of using only contracting bricks together with contracting combinations has guided us to an efficient way of generating normometric saccades in all direction and simulates the activity of known SC and SBG neurons. The contraction of the whole system is simply derived from the properties described in section III. That is, we first notice that the analysis on convex region enable to study the linear part of our model only. We then isolate the real loops of the model by identifying all the hierarchical combinations. To conclude, we remark that the remaining loops are all instances of negative feedback.

| | | | | | |
|------------------|-------|-------------------|---------|-------------------|--------|
| τ | $5ms$ | τ_{Sat} | $100ms$ | t_0 | $70ms$ |
| ϵ_{OPN} | 100 | ϵ_{trig} | 400 | ϵ_{stop} | 200 |
| w_{Vis}^{LLB} | 0.005 | w_{OPN}^{Mot} | 40 | w_{OPN}^{BN} | 40 |
| w_{Mot}^{Int} | 0.002 | w_{Sat}^{Mot} | 8 | w_{BN}^{TN} | 0.05 |
| w_{BN}^{MN} | 1.52 | w_{MN}^{θ} | 4.07 | | |

TABLE I
PARAMETERS OF THE SC MODEL

The use of computationally inexpensive rate-coding artificial neurons allows real-time computation of the model and thus its use on robotic platforms. A preliminary implementation of the model on an anthropomorphic robotic head has already been done in order to evaluate its relevance with regards to robotic active vision systems [32].

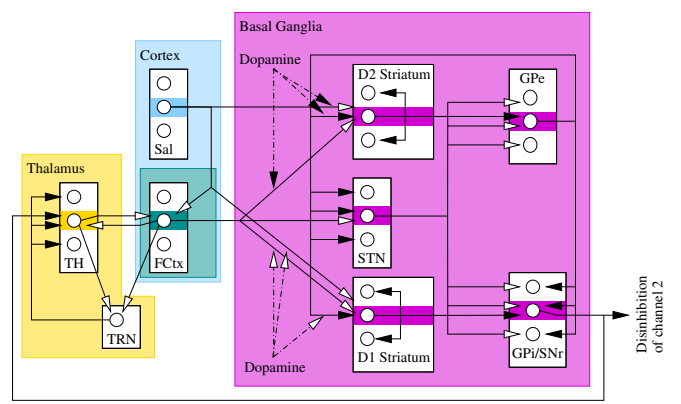


Fig. 3. CBGTC loop model. Three channels competing for selection are represented; for clarity, the projections of the second channel only (the shaded one) are represented; white arrowheads: excitatory projections; black arrowheads: inhibitory projections; D1 and D2: neurons of the striatum with two respective types of dopamine receptors; STN: subthalamic nucleus; GPe: external segment of the globus pallidus; GPi/SNr: internal segment of the globus pallidus and substantia nigra pars reticulata; TH: thalamic nucleus; TRN: thalamic reticular nucleus; FCtx: frontal cortical area involved in the loop; Sal: cortical areas providing the external input (or *Saliences*). Dopamine level has a modulatory effect on the striatal input.

V. CONTRACTING MODEL OF THE CORTICO-BASO-THALAMO-CORTICAL LOOPS

The basal ganglia (BG) are a set of interconnected sub-cortical nuclei, common to all vertebrates, and thought to constitute a generic evolution solution to the problem of selection. They interact with the cortex within parallel cortico-baso-thalamo-cortical loops (CBGTC, like the FEF-BG-VL-FEF loop represented in Fig. 1) [33]. The interest of using BG models as action selection architectures for autonomous robots has been assessed in previous studies [34], [35], [36], [37]. However these studies were based on the model proposed by [38], [39] (the GPR model), which seems to be contracting only in relatively restrictive conditions [40].

The role of the BG in the saccadic circuitry seems to be the selection of the target of the upcoming saccade among the multiple points of interest present in the visual field. Each target competing for selection is represented by a channel inside the BG, and is considered selected when it is disinhibited [41]. At rest, the BG tonically inhibits the collicular motor maps. When one of them wins the competition, the inhibition of the corresponding map area is removed, allowing the generation of the saccade.

We proposed a new BG model [40] including usually neglected connections, which was proved to be contracting, and used it as the basis of a model of the CBGTC loops [42]. The BG model selects the channel with the highest input (or salience) using three mechanisms: recurrent lateral inhibitions in the input nuclei (D1 and D2 striatum), off-center on-surround architectures in the D1-STN-GPi and D2-STN-GPe complexes, reinforced by negative feedback loops between GPi and D1, and GPe and D2. Given known thalamus anatomy and relationships with cortex and basal ganglia [43], a simple thalamo-cortical module was added

to the existing BG model (see Fig. 3, thalamus and cortex boxes). The Th-FCtx excitatory loop is proposed to have a role of amplification of the sensory signal, its net gain is however kept under 1, so that it amplifies the cortical signal without saturating (and thus avoid indefinitely self-sustained activity).

The inhibitory projections of the BG onto the thalamus favors a selective amplification of the winning channels. The interest of such an architecture is that in the frontal cortex, the selected channel has its activity amplified, but the information about the other channels isn't lost. On the contrary, the subcortical target circuits of the BG (including the SC) are under very selective inhibition, so that the circuit corresponding to the winning channel only is disinhibited.

The model sketched in Fig. 3 is fully described by the following definition of the input of the different classes of leaky-integrators neurons used (the values of the parameters are given in table II). For clarity, we split the description of the basal ganglia part on the one hand

$$I_i^{D1} = (1 + \lambda)(w_{Sal}^{D1}S_i + w_{FCtx}^{D1}y_i^{FCtx} - w_{GPe}^{D1}y_i^{GPe}) - w_{LatD1} \sum_{j \neq i}^N y_j^{D1}$$

$$I_i^{D2} = (1 - \lambda)(w_{Sal}^{D2}S_i + w_{FCtx}^{D2}y_i^{FCtx} - w_{GPe}^{D2}y_i^{GPe}) - w_{LatD2} \sum_{j \neq i}^N y_j^{D2}$$

$$I_i^{STN} = w_{FCtx}^{STN}y_i^{FCtx} - w_{GPe}^{STN} \sum_{j=1}^N y_j^{GPe}$$

$$I_i^{GPe} = -w_{D2}^{GPe}y_i^{D2} + w_{STN}^{GPe} \sum_{j=1}^N y_j^{STN}$$

$$I_i^{GPe} = -w_{D1}^{GPe}y_i^{D1} + w_{STN}^{GPe} \sum_{j=1}^N y_j^{STN} - w_{GPe}^{GPe} \sum_{j=1}^N y_j^{GPe}$$

On the other, we can describe the Th-FCtx loop by the three following equations

$$I_i^{FCtx} = S_i + w_{TH}^{FCtx}y_i^{TH}$$

$$I_i^{TH} = -w_{GPe}^{TH}y_i^{GPe} - w_{TRN}^{TH}y_i^{TRN} + w_{FCtx}^{TH}y_i^{FCtx}$$

$$I_i^{TRN} = \sum_{j=1}^N (w_{FCtx}^{TRN}y_j^{FCtx} + w_{TH}^{TRN}y_j^{TH})$$

The contraction of the model has already been proved (we refer the reader to [42] for technical details) and we just mention here the typical kind of equations that arise from contraction analysis. Providing some constraints on the projections weights, the contracting rate of basal ganglia (τ_{BG}) and of the Th-FCtx loop (τ_{TC}) are

$$\tau_{BG} = 1 - (0.5w_{LatD2} + \sqrt{0.25w_{LatD2}^2 + w_{D2}^{GPe}w_{GPe}^{D2}})$$

$$\tau_{TC} = 1 - 0.5(w_{FCtx}^{TH}w_{TH}^{FCtx} + \sqrt{w_{FCtx}^{TH}^2w_{TH}^{FCtx}^2 + w_{FCtx}^{TRN}^2})$$

And for the whole system to be contracting, a last condition

on the global loop is required:

$$w_{GPe}^{TH} \max(w_{FCtx}^{D1}, w_{FCtx}^{D2}, w_{FCtx}^{STN}) < 4\tau_{BG}\tau_{TC}$$

The ability of the system to (1) perform clear selection of the channel with the largest salience, and (2) significantly amplify the signal in the frontal cortex of this channel only, without any influence of the initial state (a property implied by contraction), was tested by feeding a 6-channels system with a sequence of 1000 randomly drawn salience vectors successively, without resetting the system. Concerning

TABLE II
PARAMETERS OF THE CBGTC MODEL.

| | | | | | |
|------------------|------|------------------|------|-----------------|--------|
| w_{Sal}^{D1} | 3.6 | w_{GPe}^{STN} | 0.35 | τ | 0.003s |
| w_{Sal}^{D2} | 3.6 | w_{GPe}^{GPe} | 0.08 | λ | 0.2 |
| w_{LatD1} | 0.4 | w_{D2}^{GPe} | 0.7 | w_{TH}^{FCtx} | 0.6 |
| w_{LatD2} | 0.4 | w_{D1}^{GPe} | 1 | w_{FCtx}^{TH} | 0.6 |
| w_{GPe}^{D1} | 1 | w_{STN}^{GPe} | 0.35 | w_{GPe}^{TH} | 0.5 |
| w_{GPe}^{D2} | 1 | w_{STN}^{GPe} | 0.35 | w_{TRN}^{TH} | 0.35 |
| w_{FCtx}^{TRN} | 0.35 | w_{TH}^{TRN} | 0.35 | w_{FCtx}^{D1} | 0.4 |
| w_{FCtx}^{D2} | 0.4 | w_{FCtx}^{STN} | 2.32 | | |

selection, the results are that the channel with maximum salience is always selected (for 16.7% of the input vectors, the closest competitor channel is also selected, when the difference between the two saliences is small). Concerning amplification of the signal in the frontal cortex, we obtain that, in average, the frontal cortex activity of the selected channels is amplified by 44.4%, while the amplification of the others is of 13% only.

Finally, this new model has been tested as a robotic action selection mechanism in a minimal survival task, similar to the one used in the evaluation of the GPR model [35]. It has been compared to a simple ‘‘If-Then-Else’’ algorithm without memory but able to solve the task [44]. It revealed to have similar properties of behavioral dithering avoidance and energy saving as those exhibited for the GPR model in [35].

VI. CONCLUSION AND FUTURE WORK

We presented a research program dedicated to testing the hypothesis that contraction is a stability property verified by the many interconnected nonlinear dynamic systems composing the brain. This program is focused on the long-studied saccadic circuitry, implying all brain levels, from the cortex to the brainstem. We described the already developed models of the cortico-baso-thalamo-cortical loops on the one hand, and the superior colliculus and reticular formation saccade burst generators on the other hand. We also evoked preliminary robotic implementations of these models in active vision systems.

These two models must now be connected together in order to produce a first contracting saccadic circuitry model from cortex down to reticular formation, updating the model

of [45]. The addition of a contracting cerebellar module inspired by recent proposals [46] is the next step of our research program, which should add the adaptivity and on-line trajectory control necessary for robust and efficient robotic implementations. From a neuroscience point of view, we will also study whether it is necessary to consider some of the modules at a finer time scale, using spike based computation in place of rate coding. Finally, of course, we expect robotic implementation on humanoid systems to be a key element of the end results.

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