The Neural Optimal Control Hierarchy

Travis DeWolf
tdewolf@uwaterloo.ca
University of Waterloo

The NOCH framework was designed to serve as a foundation for development of models of neural motor control. The driving purpose behind the NOCH is bridging the gap between the control theory and neuroscience research in the field of motor control. This is done by identifying the underlying functions in control theory models of motor control and examining the structure/connections of the neural systems from neuroscience, identifying potential mappings and biological implementations of required processes.

1 NOCH: A brief summary

A block diagram of the NOCH framework is displayed in Figure 1. The numbering on this figure is used to aid description, and does not indicate sequential information flow. For additional details see [3].

1 - Premotor cortex (PM) and the Supplementary Motor Area (SMA)

The premotor cortex (PM) and the supplementary motor area (SMA) integrate sensory information and specify target(s) in a low-dimensional, end-effector agnostic, and scale-free space. End-effector agnostic means that at this stage, no lower-level dynamics for any limbs or body segments that might carry out the action are considered. It is strictly a high-level space, which may specify control signals in terms of, for example, 3D end-point position. Scale-free refers to the fact that solutions found for linear Bellman controllers for optimal movement in an area of a particular size can be subsequently manipulated by rescaling, due to the fact that this high-level space is end-effector agnostic [3].

An example of PM/SMA function in arm reaching begins with the planning of an optimal path from current hand position to target, which incorporates information from the environment, such as obstacle position. Previously learned motor components (i.e., synergies), are used as as a basis, and linearly combined through weighted summation to compose the desired movement, as described in . If the desired movement cannot be created from the available set of basis synergies, the system may explore new paths through space to determine a satisfactory trajectory. These areas act as the highest levels in a motor control hierarchy that proceeds through M1 and eventually to muscle activations.

2 - Basal Ganglia

Recently, the basal ganglia has been characterized as a winner-take-all (WTA) circuit [5], as responsible for scaling movements or providing an 'energy vigor' term [9], and as performing dimension reduction [1]. Spiking neuron implementations that employ the same methods of neural simulation employed here have been used to construct a WTA circuit model that has strong matches to neural timing data [7], and can incorporate both movement scaling and dimension reduction [8]. Consequently, in the NOCH, the basal ganglia is taken to weight movement synergies for the generation of novel actions, perform dimension reduction to extract the salient features of a space for training cortical hierarchies and developing new synergies, and scale movement during directed action.

3 - Cerebellum

The cerebellum is widely regarded as an adaptation device, performing online error correction, and is thus often taken as the site for the storage of internal models [4, 2, 10, 6]. In the NOCH, the cerebellum is taken to play a similar role. While in the cortex movement synergies stored are for well-learned environments and situations operating under normal system dynamics, the cerebellum stores synergies that allow the system to adapt to new environments and dynamics, and learn or recall situations to adapt current movements appropriately based on sensory feedback. Additionally, the cerebellum plays a central role in correcting for noise and other perturbations, correcting movement errors to bring the system to target states as specified

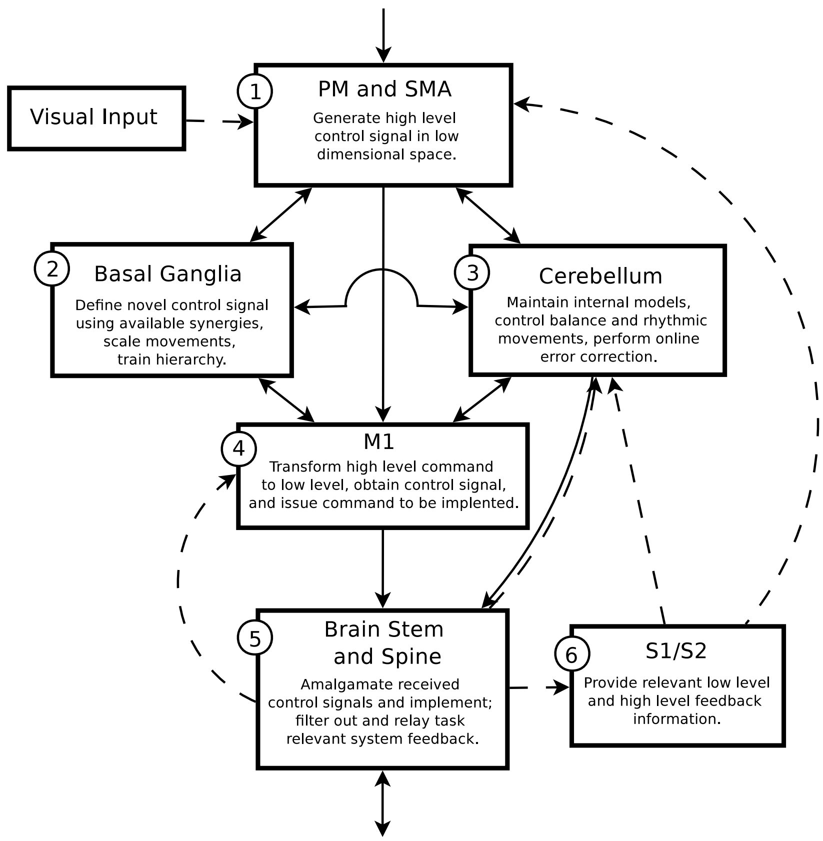

Figure 1: The NOCH framework. This diagram embodies a high-level description of the central hypotheses that comprise the Neural Optimal Control Hierarchy (NOCH). The numbering on this figure is used to aid description, and does not indicate sequential information flow. See text for details.

by higher-level controllers. Consequently, the cerebellum is also responsible for control of automatic balance and rhythmic movements, such as locomotion.

4 - Primary Motor Cortex

In the NOCH, the primary motor cortex (M1) is understood as containing the lower-levels of a hierarchical control system. The primary motor cortex thus acts as a hierarchy that accepts high-level commands, such as end-effector force in 3D space, from the PM and SMA, and translates them through hierarchical levels to muscle activation signals. The main functional role of this hierarchy is to map high-level control signals to low-level muscle activations in an efficient manner, allowing the PM and SMA to develop control signals in a reduced, lower-dimensional space. The synergies at each level are assumed to change over time, as skills are developed or lost.

5 - Brain Stem & Spinal Cord

For our purposes, the brain stem acts as a gateway for efferent motor command and afferent sensory input pathways. Here, descending commands from different neural systems in the NOCH can be combined and passed on to the spinal neural circuits and motor neurons for execution.

6 - Sensory Cortices (S1/S2)

The primary sensory cortex (S1) is used for sensory feedback amalgamation and processing in the NOCH, serving to produce multi-modal feedback which is then relayed to the motor areas such as M1 and the cerebellum. Both of these systems are taken to work in lower-level, higher-dimensional spaces, and are thus in a position to incorporate appropriate feedback signals into the working motor plan. The secondary sensory cortex (S2) is responsible for transforming the information from the primary sensory cortex into high-level sensory feedback information, which is then relayed to the high-levels of the M1 hierarchy, as well as PM and SMA. Additionally, S1 and S2 perform a noise filtering on sensory feedback, combining different types of feedback to arrive at the most reliable prediction of body and environment state, analogous to the function of a Kalman filter.

References

[1] Izhar Bar-Gad, Genela Morris, and Hagai Bergman. Information processing, dimensionality reduction and reinforcement learning in the basal ganglia. *Progress in neurobiology*, 71(6):439–73, December 2003.

[2] A Bastian. Learning to predict the future: the cerebellum adapts feedforward movement control. *Current Opinions in Neurobiology*, 16(6):645–649, 2006.

[3] Travis DeWolf. *NOCH : A framework for biologically plausible models of neural motor control*. PhD thesis, University of Waterloo, 2010.

[4] K Doya. What are the computations of the cerebellum, the basal ganglia and the cerebral cortex. *Neural Networks*, 12:961–974, 1999.

[5] K Gurney, T J Prescott, and P Redgrave. a. A computational model of action selection in the basal ganglia. I. A new functional anatomy. *Biol. Cybern.*, 84:401–410, 2001.

[6] M Kawato. Internal models for motor control and trajectory planning Mitsuo Kawato. *Current Opinion in Neurobiology*, pages 718–727, 1999.

[7] Terrence C Stewart, Xuan Choo, and Chris Eliasmith. Dynamic Behaviour of a Spiking Model of Action Selection in the Basal Ganglia. *Current*, 2010.

[8] Bryan Tripp. *A search for principles of basal ganglia function*. PhD thesis, University of Waterloo, 2009.

[9] Robert S Turner, Michel Desmurget, Corresponding Turner, and Robert S. Basal ganglia contributions to motor control : a vigorous tutor. *Current Opinion in Neurobiology*, 20(6):704–716, 2010.

[10] D M Wolpert, R C Miall, and M Kawato. Internal models in the cerebellum. *Trends in Cognitive Sciences*, 2:338–347, 1998.