The Neural Optimal Control Hierarchy

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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.

0.1 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 space (i.e. end-effector space).

An example of PM/SMA function in arm reaching is planning an optimal path from the current position of the hand to the target, incorporating information from the environment, such as obstacle position. Previously learned motor components (i.e., synergies), are used as basis functions, and combined through weighted summation to compose the desired movement. This process is described in detail in [?]. The PM/SMA areas act as the highest levels in the motor hierarchy, generating signals that proceed through M1, and eventually to motor neurons, causing muscle activation.

2 - Basal Ganglia

The basal ganglia has been characterized in several ways: 1) As a winner-take-all (WTA) circuit [5], 2) as responsible for scaling movements or providing an 'energy vigor' term [9], 3) and as performing dimension reduction [1]. Recently, spiking neuron implementations of the WTA circuit model have been made capable of generating results on a timeline consistent with neural timing data [?], lending support to these claims. Interestingly, the WTA circuit can also be adapted to provide a weighting over a set of input based on their similarity to a desired signal, rather than choosing a single winner. In the NOCH, the basal ganglia is taken as a system capable of learning to approximate an incoming signal given a set of component signals, on a short time-scale. As best as possible, the basal ganglia weights available movement synergies for the generation of novel actions, adjusting the weights over the component set based on sampling state information as the system repeatedly attempts to carry out a given action.

3 - Cerebellum

The cerebellum is widely regarded as having three main functions. Two of these are related to its function as an adaptation device: 1) Performing online error correction, and 2) generating and storing models of internal and external dynamics [4, 2, 10, 6]. The third function is the control and modulation of spinal circuitry and central pattern generators, involved in processes that control balance and rhythmic actions, such as locomotion. In the NOCH, the former two functions of the cerebellum are modeled, while the third is acknowledged but assumed the function of an unmodeled part of the cerebellum.

In the cortex, movement synergies are stored for well-learned environments and situations operating under normal system dynamics. The cerebellum is proposed to store synergies which 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 by higher-level controllers. To do this, the cerebellum develops a mapping from low-level state and commands to high-level
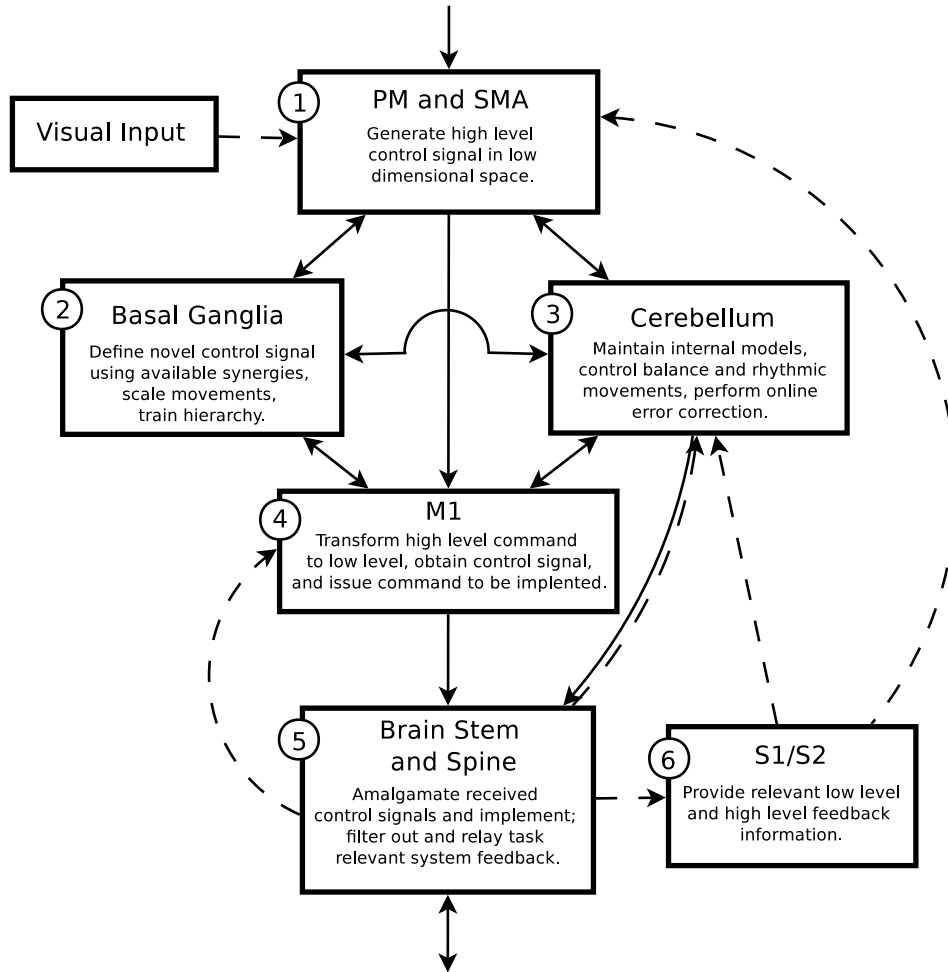
Figure 1: The NOCH framework. This diagram embodies a high-level description of the central hypotheses that comprise the Neural Optimal Control Hierarchy (NOCH). The numbering on this figure is used to aid description, and does not indicate sequential information flow. See text for details.

state acceleration by dividing the state space up into areas where the dynamics can be captured with a simple linear model, and performing local linear regression on the sampled data. As this forward model is built up, the cerebellum also learns the set of corresponding linear controllers, to generate a low-level command given the low-level state and a desired high-level acceleration.

4 - Primary Motor Cortex

In the NOCH, the primary motor cortex (M1) houses the lower-levels of a hierarchical control system. These can be understood as the muscle specific synergies, as opposed to the abstracted PM/SMA synergies operating in end-effector space. These M1 synergies are built up from the basic linear controllers developed in the cerebellum, and are much more complex, but cover a much more restricted area of state space. The primary motor cortex thus accepts abstract, high-level commands, such as end-effector force in 3D space, from the PM and SMA, and generates muscle activation signals. The main functional role of this hierarchy is to map high-level control signals to low-level muscle activations efficiently, allowing the PM and SMA to generate optimal control signals in low-dimensional space, as opposed to the high-dimensional muscle space. These M1 synergies are understood 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 commands 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.

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