Bottom-Up Modeling of Cerebro-Cerebellar Interaction

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The Problem: To obtain systems engineering models of the interaction between the brain's principal motor executive center, the cerebrum, and its principal 'coordinating' center, the cerebellum.

Motivation: Increasing scientific data about the primate cerebellum appears to show that the organ provides highly important assistance to the cerebrum in many domains. These include the scaling, coordinating, timing and adaptation of body stabilization, movement and force control, autonomic and emotional responses as well as a variety of cognitive processes. Intriguingly, the microscopic neural architectures of the different cerebellar subregions thought to mediate these different activities are almost identical. This suggests strongly that some type of fundamental cerebellar signal processing is highly beneficial, if not critical, to most human executive and perhaps many perceptual functions. A detailed, quantitative understanding of the interactions between the cerebrum and cerebellum should the be of considerable value in understanding brain function and dysfunction, for developing artificially intelligent systems, as well as for designing neurodiagnostic and neuroprosthetic devices.

Previous work: Basic engineering models have been developed to describe cerebro- cerebellar interaction in the control of single joint and two-joint limb stabilization and movement [3, 2]. These models adhere to known neuroanatomy and spinomuscular physiology and propose quantitative descriptions of the operation of cerebral and cerebellar neural pathways. To date, these models are able to describe both the input-output motor control behavior as well as several internal neural signals that have been recorded in behaving primates. It also appears that these models are beginning to explain the mechanisms of a variety of motor control deficits associated with cerebellar disease and injury. From an engineering perspective, the models point to a critical role of the cerebellum in adaptive linear control, prediction and stabilization with respect to feedback loop delays.

Approach: Because of the relatively recent availability of much more powerful scientific computer based simulation, it is now feasible to pursue true bottom-up modeling and analysis of the nervous system. Thus, the initial models described above are being systematically extended and deepened to incorporate increasing numbers of subsystems within the cerebro-cerebellar interaction. The approach is one of a tight iteration between analysis, simulation and experiment: review of biological literature, formulation of initial engineering model, (*) testing of model by comparing simulated performance with available data, modification of model and design specific new behavioral experiments, human and animal experiments, collection and analysis of data (loop to *). As with most neuroengineering projects, this research involves close interaction with other laboratories in systems engineering, artificial intelligence, brain and cognitive science and Health Sciences and Technology at MIT and elsewhere.

Difficulty: Both animal behavior, and animal nervous systems are clearly very complex. There is also an enormous amount of potentially relevant data within the biological literature. Development of models that are scientifically valid and interpretable from an engineering perspective requires review and distillation of a wide range of studies in the neurophysiological, neuroanatomical, neuropsychological as well as neurological literature and evaluating these in terms of concepts in systems engineering and computer science. Then careful experiments must be devised to isolate behaviors that will clarify pivotal questions in the formulation and refinement of the models. Multidisciplinary expertise must be brought to bear. Hence, coordination of projects between a group of laboratories can be key.

Impact: The current line of investigation, namely the development of substantially linear adaptive control models of cerebro-cerebellar interaction continues to appear promising. Increasing numbers of aspects of human postural stabilization and movement control both in health and disease states appear to be explained including features of limb movement and upright balance [1]. The models, formulated and tested in MATLAB computing software

are highly amenable to engineering analyses and to artificial – especially robotic – system design. Although the requirement of physiological accuracy renders progress somewhat painstaking, it essentially assures that the eventual solutions will be of significant value to artificial intelligence and to medicine.

Future work: 1) Current models are to be subjected to increasingly rigorous testing for scientific validity. This primarily involves determining: a) whether the model's input- output behavior can account qualitatively and quantitatively for an increasing number of experimentally studied human healthy and disordered motor behaviors, and b) whether the internal signals predicted to occur along each of the model's internal pathways match those that are observed in neurophysiological recordings during these behaviors. 2) Current models are to be extended to incorporate the participation of higher levels of cerebro- cerebellar function that include motor programming, timing and prediction. 3) Current and future models are to be studied from a theoretical perspective to identify the capacities and limitations, and in general, the advantages and disadvantages of natural motor system's architecture. We will consider how these findings bear upon the design of humanoid robotic systems. 4) Understanding gleaned from system modeling is also to be applied to diagnostic and therapeutic methods for neurological disorders as quickly as feasible.

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References:

[1] Sungho Jo. Application of a model of cerebellar function to the maintenance of upright posture. Master's thesis, MIT, May 2001.

[2] Steve G. Massaquoi. *Modeling the Function of the Cerebellum in Scheduled Linear Servo Control of Simple Horizontal Planar Arm Movements.* PhD thesis, MIT, March 1999.

[3] Steve G. Massaquoi and Jean-Jacques E. Slotine. The intermediate cerebellum may function as a wave-variable processor. *Neuroscience Letters*, pages 60–64, 215 1996.