Modeling and Analysis of Low-level Natural Motor Control

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The Problem: How does the animal (and especially the human) brain organize and execute control of basic postural stability and voluntary movement? Specifically, what are the signal processing roles of the spinal cord, brainstem, cerebellum, basal ganglia and cerebral cortex in the production of postures, simple movements repertoires?

Motivation: Quantitative models of the human (animal) motor control system should provide 1) better scientific understanding of natural motor control and natural executive cognition systems in general; 2) a rational basis for the development of advanced neurological diagnostic and therapeutic techniques and devices such as model-based brain imaging and implantable neuroprostheses; 3) guidelines for the design of biomimetic robots.

Previous Work: An important issue in natural motor control is determination of the precise roles of feedback signals and internal dynamic models in biological motor control systems. Recently, Wave-Variable Cerebellar Arm Control Models (WVCACMs) [1,2] have been developed to explain the nature of cerebro-spino-cerebellar cooperation in the control of single and two-joint arm movements. These models appear to explain how relatively high-performance servo control could be implemented by the central nervous system without detailed internal dynamic models despite the presence of significant signal transmission delays and relatively low arm stiffness during movement. The models also provide possible explanations for experimentally observed internal brain signals in the monkey, as well as the mechanisms of several of the clinical signs (outward manifestations) of cerebellar disorders.

Approach: The research attempts a balanced integration of neuroanatomy, neurophysiology, the neurology of movement disorders, biomechanics and engineering control theory to generate computer models that are comprehensible from all of these perspectives. In particular, models are sought that are fully consistent with known neurocircuitry and which exhibit internal signals that closely match signals observed in vivo. At the same time, the models should reproduce the motor behavior both of healthy humans and of humans who suffer from various motor system diseases. Finally, the models need to explain and predict the stability and performance characteristics of animal motor control systems. Thus, particular emphasis is placed upon obtaining models that are complex enough to capture simultaneously most general features of animal posture and movement control, but that are simple enough to be relatively easily simulated and analyzed in control theoretic terms.

This work involves 1) review of known neuroanatomy and a wide range of neurophysiological experimental results both in health and disease, in humans and animals; 2) creation of parsimonious models that are consistent with these data; 3) systematic simulation of these models to determine first, their abilities to explain existing data and second, their predictions of the characteristics of motor behaviors yet to be examined; 4) design and execution of experiments with humans, animals and robots to test model predictions; 5) correction, refinement and extension of existing models.

The studies also involve a collaboration between a number of investigators at the AI-Lab, Lab for Information and Decision Systems, the Harvard-MIT Division of Health Sciences and Technology, and the Massachusetts General Hospital having different areas of interest and emphasis: human vs. animal, theoretical vs. experimental, physiological vs. pathophysiological.

Difficulty: Natural motor behavior typically involves a large number of degrees of freedom in control system function. Humans and other animals are automatically very creative and subconsciously or semiconsciously employ a number of techniques to solve movement control problems. Therefore, experiments and analyses must be highly restrictive and focussed to elucidate the elemental system control components and properties. This necessitates very careful, detailed experimental design and generally a highly structured experimental environment. Obtaining corroboration of predictions of internal signals requires careful, expensive primate work (done by collaborators).

Impact: At their present stage, the investigations constitute basic scientific research. As such, their first contribution is to general scientific understanding of brain function. The WVCACMs suggest that piecewise linear feedback control may be a realistic description of natural low-level movement control. If so, this has implications with regard to how high-level (e.g. task-level) natural movement control, and indeed how more general executive aspects of natural cognition (e.g. self-directed thought), may be implemented. Several projects that involve more direct applications of the modeling to neurophysiological imaging and to artificial motor control are currently underway or are being planned.

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References:

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