Modeling Sensorimotor Cortical Control of Movement

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The Problem: To develop a model that can account for experimental sensorimotor cortical activity observed during a set of motor tasks executed by primates. The model should accomplish this while remaining as anatomically and physiologically accurate as possible.

Motivation: Experimental data that relates electrical activity in the brain to limb movement is fairly abundant. However, there are relatively few physiologically accurate models that describe in quantitative terms the role of the sensorimotor cortex in motor control. By developing an engineering model of sensorimotor cortical signal processing during limb movement in particular, we hope to obtain a deeper understanding of how brain-like devices provide flexible, adaptable and robust motor control. Primary applications envisioned are the design of controllers for robots and brain-machine interface-based devices.

Previous Work: Previous models of the natural motor control system such as that developed by Bullock et al. [2] and Micci-Barreca and Guenther [3] include descriptions of the role of sensorimotor cortex in motor cortex. These appropriately emphasize its importance in transforming signals in external world coordinates to those in joint or muscle length coordinates where motor control must be implemented (inverse kinematic transformation). In addition, they note that the sensorimotor cortex participates somehow in the proper distribution of activation to groups of muscles that control degrees of movement freedom that are often redundant. For example, when reaching for an object on a table, there are many different combinations of wrist, elbow and shoulder motion that can enable the hand to arrive at the target. However, these models do not take into account physiological time delays and other neuronal and plant dynamics that may be critical to actual implementation. Moreover, they require a complexity of cortical neural network structure and a type of signal processing that may not be fully realistic.

Approach: The approach has been to study the anatomy and structure of the sensorimotor regions and the neurophysiology of appropriate neuronal populations, and to survey the literature of psychophysical and kinesiological experiments. Engineering models are then proposed such that they conform to the biological structure, and generate both the observed internal signals and input-output system behavior. Simple models are explored initially, and complexity is introduced in as needed.

This year, in collaboration with Munther Dahleh at the MIT Laboratory for Information and Decision Systems, we began development of the Coarse Gain (coarsely-sampled inverse Jacobian) Recurrent Integrator Command Generator (CGRICG) model [1] to describe the mechanism of motor command generation in the sensorimotor cortex during arm reaching in the horizontal plane. The modeled circuitry processes input signals specifying target location in workspace coordinates, taken to be present in parietal cortex, and produces joint-space commands sufficient to drive a 2-joint 6-muscle arm model whose dynamics have been substantially compensated for by a model cerebellar controller. The core of the CGRICG is a thalamomotorcortical integrator that supplies a forward command signal and a recurrent efference copy to parietal regions. This signal is processed by a forward kinematic model and a differencing network assumed to exist in parietal/sensory cortex. A kinematic error signal is then sent through a parietomotor cortical distribution and scaling network that is sampled only coarsely with respect to movement direction. Simulations of the CGRICG-arm model produce qualitatively realistic features of human/primate arm movement kinematics and dynamics as well as realistic signals in sensorimotor cortical neuronal assemblies. The model extends related previous models by showing that (1) effective inverse kinematic transformation can be achieved implicitly using a relatively small number of computational units, (2) the feedback-dependent command generation process can drive realistic movements when intracortical neuronal network dynamics and delays are incorporated (3) adaptation of cortical network connection strengths to improve motion straightness may proceed without affecting final target accuracy and (4) cortical neuronal network tuning coarseness and dynamics

may have mild velocity-dependent effects on multijoint movement curvature.

Difficulty: In its full detail, the system that is being studied is a highly complex and nonlinear one. It is important to abstract this system in a fashion that allows us to retain the essential principles that are core to its operation. Thus, a large amount of neurophysiological and neuroanatomical detail must be dispensed with while attempting to preserve the true nature and capabilities of the system, such as stable performance in the context of neural transmission delays and phase lags, as well as flexible adaptation and learning. At this point, although the the CGRICG model provides a simpler proposal for sensorimotor cortical coordinate transformation, and verifies that limb dynamics can be handled satisfactorily by the neural networks, it does not yet account for control of redundant degrees of freedom or provide an explicit mechanism for motor learning.

Impact: This work should contribute fundamentally to the design of brain-like motor controllers for robots and brain-machine interface-based machines.

References:

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