580.431/631 Computational Motor Control

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Meeting times: Tuesday/Thursday 4:00 PM

Maryland 217

This course blends robotics theory, control theory, neural networks theory, and neuroscience to understand in some depth the primate motor system. Our goal is to understand how the brain uses vision and other sensory feedback to plan and control movements of the limb.

Sept. 4. Introduction

Sept. 9. Muscle models and joint torques

Sept. 11. Muscle afferents and control of feedback

Sept. 16. Limb stability: equilibrium points and stiffness

Sept. 18. Computing end-effector location

Sept. 23. Computing target location

Sept. 25. Computing a difference vector I

Sept. 30. Computing a difference vector II

Oct. 2. Representing the difference vector

Oct. 7. Planning joint displacements

Oct. 9. Learning to align vision and proprioception

Oct. 14. Generalization from local examples

Oct. 16. Remapping and forward models

Oct. 21. Characteristics of movement trajectories

Oct. 23. Feedback control via a next-state planner

Oct. 28. Redundancy

Oct. 30. Dynamics

Nov. 4. Internal models of dynamics

Nov. 6. Learning and generalization of internal models

Nov. 11. No class

Nov. 18. Consolidation of internal models

Nov. 20. Filtering and learning mechanisms. Project proposal deadline.

Nov. 25. Learning internal models in the cerebellum

Dec. 2. Action selection

Dec. 4. Final examination

Dec. 19. Project deadline.

Grading:

Undergraduates: Max{(60% Homework, 40% final) OR (40% Homework, 60% final)}

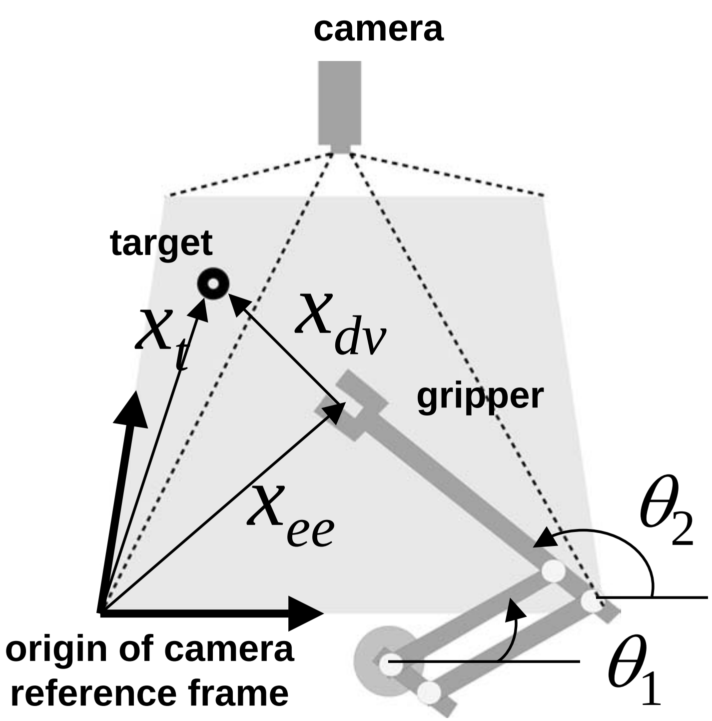
Graduate students: 40% Homework, 30% final, 30% project

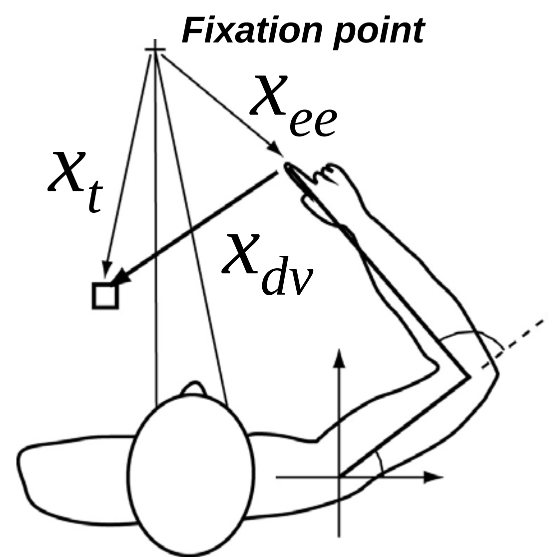
What separates plants and animals is that animals can move. To control movement, multi-cell organisms developed a nervous system.

Development of the nervous system began when multi-cell organisms began to move.

The sea squirt: In larval form, is briefly free swimming and is equipped with a brain-like structure of 300 cells. Upon finding a suitable substrate, it buries its head and starts absorbing most of its own brain.

Goal of the course: understanding how the primate brain controls movements of the arm





Building a computational theory of motor control

Lord Kelvin: “When you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.”

A computational theory clarifies what problem is being solved and why. It investigates the natural constraints that the physical world imposes on the solution to the problem.

Ellen Hildreth and John Hollerbach: “It is often true that before we can understand how a biological system solves an information processing problem, we must understand in sufficient detail at least one way that the problem can be solved, whether or not it is a solution for the biological system.”

What generates force and feedback?

Muscles convert chemical energy into force and act like an integrated system of springs, dampers, and force generators. We will describe the relationship between linear forces, as produced by muscles, and torques generated at the joints. Muscle fibers not only generate force, but also give rise to feedback signals that convey information about forces and muscle lengths to the CNS.

What maintains limb stability?

Pairs of muscles act against each other. This antagonist architecture produces an equilibrium point—a balance of forces—which helps stabilize the limb. The passive, spring-like properties of your limb promote its stability, but your CNS also uses reflexes to stabilize the limb. These mechanisms maintain your hand at a reach target or in a given direction of pointing.

How does the brain compute location of the limb?

The problem of forward kinematics: computing location of the hand in visual coordinates from proprioceptive information from the arm, neck, and eye muscles.

How does the brain compute location of the target of the reach?

In computing target location, your CNS combines information about location of the target on the retina with information about eye and head orientation. Neurons in the posterior parietal cortex encode this information in a multiplicative way.

How do the motor areas of the brain compute a plan of movement?

The difference vector represents a high-level plan for movement, which specifies a displacement of an end effector from its current location to a target's location. Does it correspond to a movement that your CNS will make with the hand, with the eye, or with some other part of your body? Does it reflect a movement the CNS might make or definitely will make? And what parts of the CNS play the most direct role in formulating this plan? We will present evidence that areas in the posterior parietal cortex, acting in close concert with the frontal motor areas, participate in computing the motor plan.

How is the plan transformed into motor commands?

Motor areas of the frontal lobe transform the high-level motor plan of reaching, corresponding to a difference vector, into joint angle changes and force motor commands. These transformations depend on internal models of the limb and the external world.

How is vision aligned with proprioception?

To represent hand location in visual coordinates, your CNS must aligns proprioceptive inputs about joint angles and muscle lengths with visual inputs about where the hand appears in fixation-centered space for that pattern of proprioceptive inputs. The CNS needs to recalibrate these computational maps whenever something alters the visual feedback of end-effector location

How are estimates of limb and target position updated when the eyes or the limb move?

Reaching and pointing movements involve continuous monitoring of target- and end-effector location in fixation-centered coordinates with the goal of reducing the difference vector to zero. Your CNS re-computes the kinematic maps that estimate target- and end-effector location as the eyes, targets and end effector move. Because this remapping depends on a copy of motor commands to the eyes, the head, and the arm, your CNS can update these estimates predictively. Systems that predict consequences of motor commands in sensory coordinates are called *forward models*. Forward models may also underlie your ability to imagine movements.

How are trajectories planned and controlled?

A reaching or pointing movement can entail an infinite number of trajectories from the end effector’s starting location to the target. However, for most reaching and pointing movements, your CNS plans the movement so that the end effector moves along just one of these trajectories: an approximately straight path with a smooth, unimodal velocity profile.

Smooth hand trajectories may be an emergent property of a feedback control system that plans for a desired change in the state of the limb based on an estimate of its current location and an estimate of current location of the goal. Such a feedback-dependent next-state planner allows the nervous system to smoothly respond to unexpected changes in goals or perturbations to the limb. However, because the plan may be specified in fixation-centered coordinates, it still needs to be translated into the intrinsic coordinate system of the limb before it can be executed.

How do we learn dynamics of the external world?

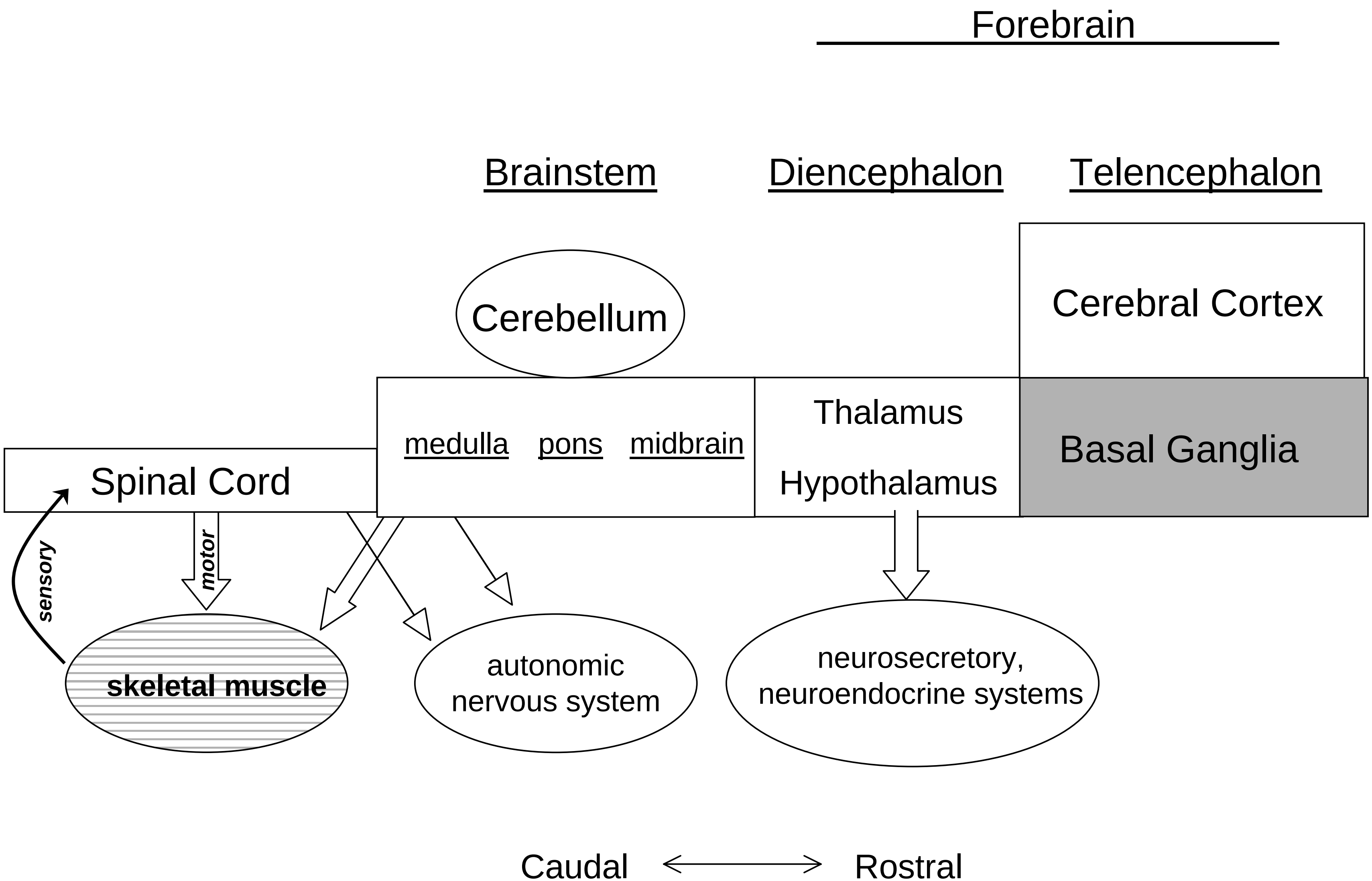
In computing an internal model of dynamics, your CNS maps limb states to forces. Patterns of generalization suggest that in this map, limb states are represented in intrinsic coordinates such as joint angles or muscle lengths. Passage of time alters the representation of internal models. With sleep and with passage of time, functional properties of motor skills change.

What are the mechanisms of error reduction?

The cerebellum and basal ganglia both function to correct errors, but of different types. The cerebellum functions to correct errors in predictions of self-generated sensory feedback and produces motor commands that anticipate and minimize unwanted sensory events. The learning in the basal ganglia, on the other hand, is driven by an error in predicted value of the state of the biological system. Associating value with the state of the system aids in deciding what to do at a given context, e.g., selection of feedback control policies for performance of an action.

What role does the cerebellum play in reducing errors in our actions?

When stimuli engage your reflexes, your CNS generates signals that guide learning in the cerebellum. In some cases, these stimuli are externally generated, like an air puff to the eye. In many cases, however, the inputs result from the your own actions. For example, motor commands for moving your forearm around the elbow produce torques that, due to inertial properties of the arm, also move your upper arm around the shoulder. If your goal is to move only your forearm, the movements of your upper arm are motor errors. Motor commands that move your head also carry your eyes, which could result in slippage of the image on your retina. In both cases, the cerebellum learns to anticipate these errors and produces motor commands that compensate for them. The cerebellum plays an essential role in learning internal models of dynamics.


Forebrain
Brainstem
Diencephalon
Telencephalon
Cerebellum
Cerebral Cortex
medulla
pons
midbrain
Thalamus
Hypothalamus
Basal Ganglia
Spinal Cord
sensory
motor
skeletal muscle
autonomic nervous system
neurosecretory, neuroendocrine systems
Caudal
Rostral