BMEE 4030: Neural Control Engineering
Credits: 3

Fall 2021 – Tuesday 4:10-6:40pm

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Overview:

This course focuses on the intersection of systems neuroscience and control engineering, and will provide an overview of cutting-edge applications of control theory in the nervous system, including non-linear system identification of neural circuitry in the sensory pathways, operant conditioning of cortical activity, modeling spatiotemporal cortical dynamics, and optimal state estimation of the nervous system.

The course is organized into different sections based on themes, with formal lectures on relevant topics, as well as case studies to emphasize the relevance to more global aspects of brain function, to present the current level of understanding in the field, and to identify areas of research that need to be pursued.

Course Introduction:

I. The Neuron and Brain Dynamics

- Basic cell biophysics
- Active conductance & the Hodgkin-Huxley model
- Simple neuron models
- Descriptive statistics of spike trains
- Statistical models of spike generation
- Wilson-Cowan model of cortex
- Case study: (Benucci et al., 2007; Huang et al., 2010)

II. Neural Plasticity and Learning

- Hebbian rule
- BCM theory
- Spike-timing dependent plasticity (Bi and Poo, 1998; Froemke and Dan, 2002)
- Homework Set 1

III. System Identification for Studying Information Processing in Sensory Systems

- Review of linear systems and control theory
- Review of system identification
- Review of Kalman filter and optimal state estimation
- Sensory systems: visual pathway and somatosensory pathway
- Encoding model, spike triggered average (STA), and spike triggered covariance (STC) etc.

IV. Multisensory Integration and Optimal State Estimation

- Multisensory integration and state estimation
- Sensorimotor integration

V. Non-linear Modeling of Neural System

- Non-parametric modeling: Volterra kernel and Gaussian Process approach (Kocijan, 2015).
- Homework Set 2
- Mid-term exam (closed book)
- Midterm report due

VI. Neural Feedback

- Classical conditioning and operant conditioning
- Operant conditioning control of neural activity (Fetz, 1969; Fetz and Finocchio, 1971)
- Case study: (Shibata et al., 2011)

VII. Control of Neural Activity through Electrical Micro-stimulation

- Neuronal response to electrical micro-stimulation
- Current Steering
- DBS for Parkinson's disease treatment
- Closed-loop control of Epilepsy (Berényi et al., 2012)
- Homework Set 3

VIII. Neural prostheses

- Motor prostheses
- Sensory prostheses
- Inter-brain communication (Pais-Vieira et al., 2013)
- Case Study: (Chapin et al., 1999)
- Case Study: Closed-loop sensorimotor neural prostheses. (O'Doherty et al., 2009)

Reading

P. Dayan and L. Abbott, Theoretical Neuroscience, MIT Press, 2001
S. Schiff, Neural Control Engineering, MIT Press, 2011

Benucci A, Frazor RA, Carandini M (2007) Standing Waves and Traveling Waves Distinguish Two Circuits in Visual Cortex. Neuron 55:103-117.
Berényi A, Belluscio M, Mao D, Buzsáki G (2012) Closed-Loop Control of Epilepsy by Transcranial Electrical Stimulation. Science 337:735-737.
Bi G-q, Poo M-m (1998) Synaptic Modifications in Cultured Hippocampal Neurons: Dependence on Spike Timing, Synaptic Strength, and Postsynaptic Cell Type. The Journal of Neuroscience 18:10464-10472.
Chapin JK, Moxon KA, Markowitz RS, Nicolelis MAL (1999) Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex. Nat Neurosci 2:664-670.
Fetz EE (1969) Operant Conditioning of Cortical Unit Activity. Science 163:955-958.
Fetz EE, Finocchio DV (1971) Operant Conditioning of Specific Patterns of Neural and Muscular Activity. Science 174:431-435.
Froemke RC, Dan Y (2002) Spike-timing-dependent synaptic modification induced by natural spike trains. Nature 416:433-438.
Huang X, Xu W, Liang J, Takagaki K, Gao X, Wu J-y (2010) Spiral Wave Dynamics in Neocortex. Neuron 68:978-990.
Kocijan J (2015) Modelling and Control of Dynamic Systems Using Gaussian Process Models: Springer.
O'Doherty JE, Lebedev M, Hanson TL, Fitzsimmons N, Nicolelis MAL (2009) A brain-machine interface instructed by direct intracortical microstimulation. Frontiers in Integrative Neuroscience 3.
Pais-Vieira M, Lebedev M, Kunicki C, Wang J, Nicolelis MAL (2013) A Brain-to-Brain Interface for Real-Time Sharing of Sensorimotor Information. Sci Rep 3.
Shibata K, Watanabe T, Sasaki Y, Kawato M (2011) Perceptual Learning Incepted by Decoded fMRI Neurofeedback Without Stimulus Presentation. Science 334:1413-1415.
Terman D, Rubin JE, Yew AC, Wilson CJ (2002) Activity Patterns in a Model for the Subthalamopallidal Network of the Basal Ganglia. The Journal of Neuroscience 22:2963-2976.