The Department of Mechanical Engineering presents:

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Reverse Engineering Synchronization of Brain Network Dynamics: Controllability Properties and Functional Patterns

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Reverse engineering the brain holds the promise to overhaul the quality of life of human beings and vastly benefit mankind. Further advances towards this goal will lead to the reversal of cognitive decline, the creation of pioneering neural prostheses, the establishments of novel treatments for neurological disorders, and the development of human augmentation methods. This dissertation presents a cross-disciplinary approach to the study of the structure-function relationship in neural systems. Specifically, we study the brain as a dynamical system that obeys network-wide principles, and address three foundational challenges by using mathematically grounded methods that lie at the intersection of control theory, network science, and neuroscience.

First, through the application of control and graph-theoretic paradigms, we investigate how the spatial organization of anatomical brain network components governs and constrains its complex dynamical behaviors. The first chapters are dedicated to the study of structural brain networks – that is, empirically reconstructed large-scale networks that describe the interconnection scheme between different brain regions. We reveal that brain state transitions can be controlled by a single region, and that structural brain networks possess distinct controllability profiles with respect to random networks of the same size.

Second, we address the modeling and analysis of neural activity synchronization across different brain areas – which can be described by functional brain networks. To do so, we juxtapose a bottom-up approach and a top-down approach. In the former, we utilize data-driven dynamical models to reveal that brain network dynamics synchronization is resilient to data heterogeneity, thus supporting the utilization of large heterogeneous repositories of brain recordings. In the latter, we abstract rhythmic activity of a neural system as the output of a network of diffusively coupled oscillators, and derive prescriptive conditions for the emergence of cluster synchronization. Such a phenomenon occurs when different groups of synchronized components coexist in a network, and regulates the functional interactions among network components.

Third and final, we build upon our previous findings and take aim at the tantalizing idea of controlling brain dynamics synchronization through minimally invasive local interventions. We derive a method to optimally intervene on the structural network parameters to achieve desired cluster-synchronized trajectories and, thus, prescribed functional interactions. Additionally, we show that our synchronization-based framework is robust to mismatches in network parameters, and validate it using a realistic neurovascular model to simulate neural activity and functional connectivity in the human brain.