Research Statement

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My research aims to solve optimal control and optimal intervention problems in complex physical systems, utilizing advancements in partial differential equations (PDEs) and generative AI models. By integrating precise simulation frameworks with data-driven generative AI, I develop innovative tools that effectively address intricate challenges in science and medicine.

Background

In the pursuit of addressing optimal control and intervention challenges, my research targets systems governed by complex physical dynamics, often modeled through PDEs. These systems range from fluid dynamics for aerodynamic optimizations to transcranial magnetic stimulation (TMS)-induced E-field spatio-distribution for medical therapies. Optimal control in these areas involves manipulating system inputs to achieve desired outputs with maximum efficiency and minimal error—essential for enhancing technological applications and improving therapeutic outcomes. In contexts such as fluid dynamics, where control theory is well-understood, my integration of generative AI not only deepens understanding of spatiotemporal dynamics but also opens avenues for more efficient solutions than those provided by control theory alone. Conversely, in areas like neurostimulation, where control theory is less defined, my approach enables the creation of generative models that simulate a vast array of previously prohibitively expensive scenarios. This capability allows for the exploration of counterfactuals in near real-time—a significant improvement over traditional experimental approaches, where a single simulation on a personalized head model can take several hours to a day. Efficient counterfactual generation allows researchers to test 'what-if' conditions to refine stimulation strategies. My research goal is to integrate control theory with generative AI to harness their strengths for enhanced system design, optimization, and adaptability in applications such as aerodynamics and neurostimulation. Ultimately, this work advances the adaptability, robustness, and resilience of control strategies across interdisciplinary fields.

Past Research

Control and optimization of partial differential equations: During my doctoral research, I developed and analyzed discontinuous finite volume methods for solving distributed optimal control problems governed by partial differential equations (PDEs) under pointwise control constraints. These PDEs encompassed semilinear elliptic, parabolic, hyperbolic problems, and Brinkman equations, modeling a wide range of real-world applications. My work focused on the discretization of state and costate variables using piecewise linear discontinuous finite volume schemes and explored three strategies for control approximation: the variational discretization approach, piecewise constant, and piecewise linear discretizations. Employing an optimize-then-discretize approach to handle the non-symmetric nature of the discrete optimal systems, I derived a priori error estimates

in natural norms for control, state, and costate variables [1, 2, 3, 4, 5, 6]. The accuracy and efficiency of the proposed schemes were validated through numerical experiments, confirming the theoretical convergence rates. The broader applications of this research spanned laser thermotherapy for cancer treatment, drug kinetics, complex brain dynamics, tissue engineering optimization, aircraft shape design, and enhanced oil recovery in petroleum engineering. Notably, I extended the methods to address control problems for hydrocarbon extraction using immiscible fluid injection in reservoirs [7] and linear poroelasticity equations modeling blood flow through the beating myocardium [8]. These contributions highlighted the versatility and applicability of my work in both engineering and biological systems.
Feedback stabilization of the Boussinesq system (Airbus project): In my previous postdoctoral position, I extended foundational work in control and optimization to address unstable fluid dynamics. My research focused on developing efficient feedback control laws for numerical stabilization of the Boussinesq system [9], which models non-isothermal fluid flows and is known for its high nonlinearity and instability. We constructed a feedback control law using a projected linearized system around an unstable stationary solution and solved a small-dimensional Riccati equation. Through various experiments, I demonstrated that these feedback controls effectively stabilized flow and temperature locally. This research has practical implications for optimizing energy use in buildings and aircraft by managing indoor environmental factors like temperature, humidity, and air quality, essential for addressing national energy challenges and reducing greenhouse gas emissions. Additionally, in the context of the COVID-19 pandemic and potential future epidemics, modeling and controlling indoor air quality has become increasingly important, with higher hygiene standards expected to remain a priority post-pandemic. This experience with complex, nonlinear systems laid the foundation for applying generative models to these simulations, making them faster and more adaptable for real-world applications.

Nonlinearly controllable counterfactuals with diffusion: In my current postdoctoral research, I focus on advancing controllable and counterfactual generative approaches for data generation in complex physical systems, personalized healthcare, and explainable AI. Building on the latent space of diffusion model, I have developed novel techniques that enable precise and nonlinearly controllable counterfactual generation. These methods address challenges where traditional approaches relying on known causal structures or disentangled linear latent representations fall short, particularly in systems with nonlinear dynamics and unknown causal relationships. By leveraging these techniques, we generate highly realistic and controllable counterfactual data that replicate the nonlinear dynamics and spatial geometries of complex systems. For example, we validate this approach in applications such as flow past a circular cylinder in fluid dynamics and electric field modeling in transcranial magnetic stimulation (TMS). Using benchmarks like FEM-simulated datasets, we ensure high fidelity and reliability, enabling scenario testing and performance optimization without direct experimentation. This work has significant implications for treatment planning and personalized healthcare, such as refining neurostimulation protocols for treatment-resistant depression. Additionally, it advances applications in engineering, such as optimizing aerodynamic designs for greater efficiency. By addressing uncertainties and ensuring robustness, these methods enhance real-time adaptability and decision-making across diverse domains.

Research Agenda

My research agenda is focused on establishing a state-of-the-art laboratory dedicated to advancing the integration of control theory and generative AI, addressing complex challenges in fluid dynamics and neuroscience. The lab's mission is to develop innovative methods that enhance the modeling and control of complex dynamical systems by combining the mathematical rigor of control systems with the adaptability of generative models. My strategy involves actively seeking funding from prominent agencies such as the National Science Foundation (NSF), the National Institutes of Health (NIH), and leveraging the extensive grant-writing expertise of esteemed professors at your university. With a proven track record of support from organizations such as the NIH, the Airbus Foundation, and the Indian Space Research Organization, I am well-prepared and confident in my ability to secure further funding. I will actively pursuing opportunities such as the NSF CAREER, NIH R01, DOE Early Career Award, and DARPA Young Faculty Award to advance this ambitious agenda. I aim to drive cross-disciplinary advancements by collaborating with academia, industry leaders, and other research institutions to foster innovation and make impactful contributions on a global scale.

By pioneering an integrated research path that aligns with the transformative role of AI across various domains, I aim to propel forward data-driven studies in fluid dynamics and neuroscience. The first area of focus will be implementing closed-loop control in fluid dynamics to manage instabilities such as boundary layer separation and vortex shedding, significantly improving aerodynamic performance. Concurrently, in neuroscience, I plan to extend these methods to develop real-time, closed-loop control of neurostimulation devices, enabling personalized treatment of major depression. This involves creating diverse, realistic datasets using generative AI to address data scarcity and enhance the scope of our research.

A brief technical discussion of my research goal sub-topics is outlined below.

Active control of fluid flow instabilities: Fluid flow instabilities, such as boundary layer separation and vortex shedding, are significant challenges in aerodynamics that lead to increased drag and reduced performance in applications like aircraft, ships, wind turbines, and pipelines. These instabilities can cause unwanted vibrations and flow-induced structural failures. My research aims to address these issues by developing active control strategies that leverage generative models to mitigate flow instabilities and enhance overall system performance. Generative models can capture complex flow dynamics and generate predictive data, enabling the development of adaptive control techniques that use sensors to detect vortex-shedding frequencies and actuators to disrupt or synchronize the shedding patterns. This approach helps reduce associated forces and oscillations, leading to improved aerodynamic efficiency. By integrating generative models with optimization algorithms, my project will create real-time, data-driven control strategies for managing fluid instabilities, thereby boosting performance and resilience across various engineering applications. This research aligns with NSF's well-funded statutory areas, positioning it for strong support.

Personalized Neurostimulation Therapy for Depression:
Depression is a pervasive neurological disorder that frequently resists traditional treatments, significantly affecting emotional, psychological, and physical well-being. In collaboration with Prof. Logan Grosenick and Dr. Conor Liston at Weill Cornell Medicine, I am leading a transformative project that employs a personalized, closed-loop neurostimulation system using transcranial magnetic stimulation (TMS). This non-invasive method targets specific brain regions with magnetic fields, demonstrating enhanced efficacy in cases where other treatments have failed. Our approach dynamically personalizes TMS parameters through sophisticated simulations of TMS-induced electric field distributions within individualized brain models, augmented by real-time fMRI and EEG data. These datasets illuminate subtle variations in electric fields across brain structures for responders and non-responders, enabling us to precisely adjust stimulation protocols to improve treatment responsiveness. This pioneering strategy promises to significantly advance depression treatments, offering more precise, adaptive, and effective therapeutic options.
Ultimately, the lab's goal is to push the boundaries of generative neuroscience and advanced fluid

dynamics, fostering a collaborative environment that attracts talent, secures funding, and makes impactful contributions to technology and healthcare.

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