Caltech
Student-Faculty Programs

Session M Abstracts

Extensions of the Voronoi Implicit Interface Method to unstructured meshes with applications to grain boundary evolution within a 3D X-ray diffraction inversion algorithm
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Mentors: Kaushik Bhattacharya and Carter Cocke

The Voronoi Implicit Interface Method is an efficient algorithm for tracking multiple interacting phases whose motion is governed by complex physics. The method tracks any number of phase boundaries with a single unsigned distance function and uses a narrow band method to limit updates to a reduced domain near interfaces. Distances are calculated using the Fast Marching Method, an efficient algorithm for solving the Eikonal equation. While the initial Voronoi Implicit Interface Method was implemented on a Cartesian mesh, we extend the algorithm to unstructured tetrahedral meshes in the case of advection due to an externally given, time-independent velocity field. This is important since unstructured meshes provide more flexibility when working with complex geometries. The method is used as part of a forward solve in an inversion algorithm that recovers intragranular strain and orientation fields from high-energy X-ray diffraction data. The computational efficiency and accuracy of the method within the application are compared to a previously implemented naive multiple level set approach.

Are three-dimensional detonation waves in a confined domain "realistic"?
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Mentors: Guillaume Blanquart and Benjamin R. Breer

There are parameters that can affect the structure of a detonation wave such as boundary conditions and unburnt pockets of gas. However, a clear consensus on which parameters dominate remains a subject of ongoing debate. Detonation waves are inherently multi-dimensional due to intrinsic flow instabilities. 2D cases have been studied the most because computing 3D simulations using Direct Numerical Simulation (DNS) with detailed chemistry in large domains is computationally expensive. Therefore, within our 3D simulations, DNS is performed with detailed chemistry to examine specific parameters such as boundary conditions, expanded domain size and finer grid resolution to determine how the detonation structure is altered. Four configurations are evaluated: (1) symmetrical boundary conditions in the y and periodic in z, (2) fully periodic boundary conditions in y and z, (3) an expanded domain size and (4) a refined grid resolution (both using fully periodic boundary conditions). The simulations provide detailed insights through single point statistics, probability density functions (PDF) of shock speed and induction length, planar averages, 3D isosurfaces of the shock front and the power spectral density (PSD) of temporally varying quantities. Overall, we aim to understand how boundary conditions, grid size and refined grid resolution affect detonation waves within a confined space.

Validating a computational flow solver against experimental data for multi-fidelity aerodynamic shape optimization
Aritz Schube Barriola
Mentors: Steven Brunton, Matthew M. Gherman, Ana Larrañaga, and Patricia Garcia Caspueñas

This project supports the development of a multi-fidelity active learning framework for aerodynamic shape optimization, which requires understanding the cost and accuracy trade-offs among available flow-modeling tools. The work began with a technical comparison of four modeling tools spanning a wide range of computational cost and physical detail, from fast approximate methods to a general-purpose flow solver capable of resolving complex, three-dimensional turbulent flow. Based on this comparison, the general-purpose solver was selected for deeper validation. A repeatable workflow was developed for generating computational meshes around airfoil shapes and configuring the solver for efficient, accurate simulation, including changes to convergence criteria and solution-acceleration settings that substantially reduced computation time without sacrificing accuracy. This workflow was used to run approximately sixty simulations across two airfoil shapes and four flow speeds, and the results were compared against published wind-tunnel measurements. The next phase of work shifts from validation to aerodynamic shape optimization, and will involve comparing candidate optimization approaches before selecting a method for optimizing an airfoil shape to meet specified lift and drag targets.

Reduced-order temporal forecasting of Southern North Sea velocity fields
Justin J. Wu
Mentors: Steven Brunton, Matthew M. Gherman, and Freja Petersen

Ocean velocity fields are high-dimensional, making reconstruction and forecasting computationally expensive. This project investigates whether compressed representations of Southern North Sea velocity fields can reconstruct current flow states and predict future ones. Velocity snapshots were interpolated onto a 64 by 64 grid with two velocity components and represented using Proper Orthogonal Decomposition (POD), which finds dominant spatial patterns, and a convolutional autoencoder, which learns a compressed representation from the gridded data. These methods were first evaluated on reconstruction accuracy. Linear time-update models were then fit in the reduced coordinates and evaluated at forecast horizons of 1, 5, 10, and 20 steps. POD performed best for reconstruction and single-step forecasting, while the convolutional autoencoder achieved lower forecast error across longer horizons. Additional experiments tested reduced external forcing variables and a nonlinear reduced-order model, but these did not consistently improve prediction. These results suggest that representation choice strongly affects reconstruction quality and forecast stability when modeling ocean flow.

Ultrasound-induced flow control to reduce bacterial migration in urinary catheters
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Mentors: Chiara Daraio and Amanda Y. Lin

Urinary catheters can provide a pathway for bacteria to move toward the bladder and form biofilms that contribute to infection and blockage. Existing prevention strategies, including antimicrobial coatings, passive surface modifications, and active cleaning systems, often suffer from limited long-term effectiveness. In this project, we investigate whether ultrasound can manipulate the flow field inside the catheter to suppress bacterial migration along the catheter wall without altering the catheter surface. A two-dimensional catheter model was developed in COMSOL Multiphysics to simulate acoustically induced flow generated by an ultrasonic transducer. The resulting flow fields were coupled with a bacterial dynamics model to predict the spatial distribution of bacteria over time. The simulations demonstrate that ultrasound significantly modifies the near-wall flow and reduces upstream bacteria migration. By systematically varying the transducer velocity and background flow speed, we identified operating conditions that maximize downstream bacterial transport. These findings suggest that ultrasound-induced flow manipulation is a promising strategy for reducing bacterial migration and preventing biofilm formation in urinary catheters.

Laser-grown superconductors: High-Tc niobium thin films via thermal laser epitaxy
Sophia M. Benedick
Mentors: Austin J. Minnich, David S. Catherall, and Yifei Yan

Niobium (Nb) is a type-II superconductor with the highest elemental T_c of 9.2 K in bulk. Nb thin films are of interest, as they are used to create Josephson junctions for quantum computing and superconducting quantum interference devices (SQUIDs). However, because Nb has a high melting point of 2477 C, typical thin film growth techniques, such as molecular beam epitaxy (MBE) and e-beam evaporation, present challenges, including effusion cell failures and slow deposition rates. Therefore, we turn to thermal laser epitaxy. This physical vapor deposition technique directs a continuous-wave 1 kW fiber laser (1070 nm) onto a 3 mm diameter Nb target mounted inside an ultrahigh-vacuum chamber. The laser vaporizes the Nb, which then condenses on a 1 x 1 cm^2 c-plane sapphire substrate 70 mm above it. With a T_c of 9.22 K and a residual resistance ratio of 5.82, our 25 nm Nb thin film is of excellent quality. This work demonstrates the use of thermal laser epitaxy in growing high-quality high-Tc superconducting thin films, extending its application to thin film deposition of in demand materials.

Energy and momentum transport through 3D-printed graded auxetic lattice structures subjected to impact
Carlo A. Repetto
Mentors: Guruswami Ravichandran and Aditya B. Shedge

Lattice structures have been widely studied under both quasi-static and dynamic loading due to their superior mechanical properties and high energy absorption. However, the effects of geometric gradients throughout the structures are much less understood, especially for the mechanical response of auxetic lattice structures under compression. In this study, we investigate the effects of gradients in ligament thickness and ring radius on the behavior of hexachiral lattices (lattices with a negative Poisson's ratio) under quasi-static and dynamic loading. We use an automated workflow that generates graded hexachiral lattices, performs finite element analyses (FEA), and trains a machine learning (ML) model to predict the ideal geometric gradients for peak transmitted stress, specific energy absorption, and strain at peak stress. We then fabricate the optimal geometries using resin 3-D printing and experimentally test the samples with an Instron machine and a gas gun direct impact setup. In the direct impact setup, data from a strain gauge and Digital Image Correlation (DIC) are used to measure the strain and stress wave propagation through the structure. Finally, results from both tests are incorporated into the Machine Learning training data to improve the next prediction.

Real-time attentional classification using smart glasses
Nia P. Desai
Mentors: Wei Gao and Ruixiao Liu

Attentional states are the result of coordinated neural, cardiovascular, and ocular activity. However, these signals are typically analyzed independently without consideration of relationships between physiological systems. This project uses a multimodal smart-glasses platform integrating electroencephalography, photoplethysmography, and eye-tracking data to quantify and characterize attentional states. We implemented three attention tasks used to induce various attentional states and collected data from six participants. Signal-processing pipelines were developed to extract task performance and features from neural, cardiovascular, and eye image data. For the eye-tracking images, a custom landmark-based model was used to simultaneously extract pupil, blink, and eye-state features. These three data streams have been integrated into a machine-learning model to analyze features across modalities that are not apparent when analyzing signals independently. By comparing unimodal and multimodal relationships, this work aims to enable closed-loop, real-time classification of attention from interactions between neural, cardiovascular, and ocular data into a single wearable system. This work establishes a foundation for wearable systems capable of continuous attention monitoring, with potential applications in driving safety, workplace performance, healthy aging, and neurological disease.

Efficient pulse-width modulation techniques for time-reversal photoacoustic tomography
Kaan Baris Oktay
Mentors: Lihong Wang and Indrasen Bhattacharya

Time-reversal photoacoustic tomography reconstructs images by recording acoustic pressure waves generated by a laser pulse within a scattering medium and re-emitting their time-reversed versions through an ultrasound array. Because each pulse provides an independent volumetric measurement, repeated acquisitions can capture dynamic biological processes as a time-resolved image sequence with reduced motion blurring. Re-emission uses a three-level switching pattern, or tri-state pulse-width modulation (PWM), rather than a smooth analog waveform, which allows the array's high-power output stage to drive the transducers strongly enough to address the signal-to-noise limitations of time-reversal playback. Each recorded signal must therefore be converted into a switching pattern that reproduces it accurately and efficiently. This project develops faster PWM-generation methods and a preprocessing pipeline that improves reconstruction quality, including contrast-to-noise ratio, peak-to-background ratio, and target visibility. A closed-form solution reproduces the existing PWM method approximately one hundred times faster. A revised preprocessing pipeline improves signal alignment, normalization, and rejection of high-amplitude ballistic components. The assumed electrical response of the array was also compared with measurements, and a compensation method was developed to restore signal strength lost as sound travels through the imaging medium. Together, these advances provide a faster and more physically accurate pipeline for higher-resolution, deeper-tissue, and dynamic photoacoustic imaging.

Wireless neuroelectronic system for recording and stimulation in freely moving rodents
Said M. Garcia
Mentors: Anqi Zhang and Jialun Zhu

Neurological disorders are the leading cause of disability worldwide. Emerging ultrasoft neural interfaces provide tools for the modulation and monitoring of neural circuits to understand and treat these conditions. To this effort, we developed a wireless embedded system for neural recording and stimulation, designed to interface with implantable electrode arrays in freely moving rodents. The system integrates a Bluetooth Low Energy microcontroller and a 16-channel bidirectional neural recording integrated circuit on a custom 6-layer printed circuit board (22.9 mm × 34.2 mm × 1.6 mm), capable of simultaneous recording and stimulation across 16 of 32 selectable electrodes, with neural data streamed wirelessly to a host computer. A systematic board bring-up protocol was developed and executed to verify each subsystem independently before integration. The device is currently being validated and tested directly on freely moving rodents. This work establishes a wireless hardware and firmware platform for closed-loop neuroelectronic interfaces, with broader implications for minimally invasive treatment of neurological disorders.