

Combustion in porous media burners: Computational and experimental investigation of thermo-structural material response to predict burner fracture locations

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Porous media burners are a promising technology to enable stable combustion under fuel-lean conditions in gas turbine engines, reducing nitrogen oxide and carbon monoxide emissions while improving fuel efficiency. However, experimental observations with silicon carbide foam materials show that these porous ceramics experience severe thermo-mechanical loading during combustion, leading to brittle fractures, thereby limiting durability. Therefore, a computational framework predicting thermo-mechanical stresses and potential failure locations was developed using thermo-structural finite element analysis in ANSYS Mechanical. Given silicon carbide's high compressive and relatively low tensile strength, failure is evaluated using the Rankine criterion, which assumes fracture occurs when the maximum principal stress exceeds the ultimate tensile strength. Considering an engineered matrix topology of a triply periodic minimal structure, the simulations predict pyramidal planes of critical stresses under an applied temperature gradient obtained from a porous media combustion heat transfer simulation, with the highest stresses occurring at the node-to-strut transition. These stress patterns are qualitatively consistent with experimentally observed pyramidal fracture surfaces, where fractures propagate perpendicular to the strut axis at the strut-node junction. These results suggest that the model captures key thermo-mechanical loading mechanisms and provides a framework for studying geometry and topology optimization of burner designs to improve durability.

Non-deterministic categorical Lyapunov theory

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We extend an existing categorical framework for stability and Lyapunov theory of F-coalgebras to make it compatible with non-deterministic and stochastic systems. We relax some axioms of the current framework for additional flexibility. We amend the framework's limitations through two main approaches. The first approach redefines solutions flows through a lax commuting diagram (previously strictly commuting), equipping an object with a preposetal structure under which F-morphisms are preorder-preserving. A Lyapunov morphism for a system implies equistability: all solutions admit a common class K bound. The second approach uses the endofunctor's monad structure to build a functor between F-systems and id-systems, identifying a F-system f on a space E with an id-system $f^\#$ on the transition space FE . An F-algebra is used as an aggregator to transform the original norm for E and a Lyapunov morphism for f to corresponding ones for FE and $f^\#$. The resulting notion of stability for $f^\#$ depends on the aggregator chosen, providing flexibility in how stability is defined. We apply both frameworks to common classes of non-deterministic systems (Markov kernels and transition graphs), recovering known stability results (almost-sure, mean-square, L^p stability, etc.).

Categorical Lyapunov theory for nondeterministic dynamical systems

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We develop a categorical formulation of Lyapunov stability for nondeterministic discrete-time dynamical systems. Nondeterministic evolution is modeled in the Kleisli category of the powerset monad with iteration induced by Kleisli composition, while worst-case measurements are interpreted through ordered comparison objects and join aggregation. We establish Lyapunov stability criteria and study a converse construction in which stability canonically determines suitable comparison bounds.

Bandwidth-aware collaborative mapping between a humanoid and an aerial robot

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This project develops a real-time communication and shared-mapping system that enables an aerial robot to extend the perception and planning horizon of a humanoid robot without continuously transmitting high-volume sensor data. Each robot uses 3D LiDAR measurements to construct an occupancy map within a shared reference frame. Rather than transmitting complete point clouds or maps, the aerial robot transmits compressed updates representing changes to occupied and cleared regions over a low-latency wireless link. A second, reliable communication link periodically synchronizes the robots' maps to correct errors accumulated from lost or incomplete updates. This hybrid architecture combines the longer range and reliability of a lower-frequency link with the higher bandwidth of a higher-frequency link. Both robots localize within the shared map before their observations are integrated, allowing spatial information collected from different viewpoints to be consistently combined. The communication and mapping architecture was implemented and evaluated using physical hardware, LiDAR sensors, and wireless radios as a precursor to deployment on the target robotic platforms. By reducing the amount of information required to maintain a shared representation of the environment, this architecture extends the spatial context available for motion planning and may aid in coordinating behavior among heterogeneous robotic systems.

Improving the modelling of cement carbonation and carbon uptake via Multiphysics software

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The production process of concrete is a substantial contributor to carbon emissions; however, due to a set of carbonation reactions, cement also acts as a carbon sink by absorbing atmospheric CO₂. The current estimate of the mass of CO₂ that can be absorbed by cement is 40-50% of the CO₂ emitted in manufacturing cement. However, the model used in this estimate is an approximation with assumptions that are inconsistent with the real world. Our research develops a refined model incorporating more realistic porosity and atmospheric CO₂ concentrations.

By employing a finite element method (FEM) using COMSOL Multiphysics we simulate the CO₂ diffusion throughout a block cement and incorporate the carbonation reactions that are missing in the approximate model. This improved FEM model provides a more accurate assessment of the amount of carbon absorbed through time and matches experimental data more accurately than the approximate model used in global estimates. Ultimately, this research supports the development of sustainable concrete production and utilization strategies to mitigate climate change.

Roll-slip detection for robotic tactile sensing in contact-rich manipulation

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Tactile sensing enables humans to navigate their environment by identifying object geometry, material properties, and contact interactions without visual feedback. While current research provides methods for manipulative object and material identification, little work has been done on detecting force interactions in contact-rich manipulation tasks. Current methods typically rely on a single 6-axis measurement, which provides only a net resultant force and torque. This project explores whether high-resolution robotic tactile sensing can be used to detect rolling and slipping to better understand contact interactions between objects. To do so, we first constructed 2mm resolution piezoelectric tactile sensors with a silicone layer to improve shear force sensitivity. Tactile data are then collected to compare the rotational displacement of the lid to the robotic hand trajectory to distinguish rolling from slipping. A neural network is then constructed to correlate temporal tactile measurements to a roll-slip ratio to estimate the normal and frictional contact forces between the objects to guide adjustments and alignments. This research aims to establish a framework for determining the roll-slip behavior using tactile sensing for applications such as threaded lid assembly or O-ring installation for prosthetic arms and dextrous manipulation.

An iodine-referenced laser stabilization system for high-precision cavity ringdown spectroscopy of electron-enhanced atomic layer processes (EE-ALP)

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Electron-enhanced atomic layer processing (EE-ALP) uses electrons as precursors to stimulate and enhance surface chemical reactions during thin film growth. EE-ALP opens new process windows that may help to overcome the limitations of existing ALP methods. However, a fundamental understanding of the chemical mechanisms that occur during EE-ALP is lacking. This project combines a HCP electron source with an in-situ cavity ringdown spectroscopy (CRDS) system in a custom-built reaction chamber, aiming to enable characterization of gas-phase and surface chemistry during growth. One of the preliminary goals for our system was to use CRDS to observe how electron irradiation changes the radical and ion content of common ALP chamber background gases, such as methane. CRDS is an extremely sensitive technique that measures the time constant of decay for built-up laser intensity within an optical cavity. A requirement for precise CRDS is a cavity locked to a frequency-stabilized laser; stabilization ensures the laser remains resonant with the cavity in spite of environmental disturbance, giving reproducible ringdown measurements. Typically, this is achieved by referencing the laser to fine rovibrational molecular transitions. In our setup we work towards stabilizing the beam to a molecular I_2 peak, frequency-modulating the beam as it passes through an I_2 cell. We then detect the discriminator signal of the absorption peak, or of a finer feature known as a lamb dip (on the order of MHz wide), either of which we can lock to using a servo controller. Experimentation with the optical configuration and modulation parameters is ongoing in order to achieve better signal-to-noise and optimize our lock. Finally, the Pound-Drever-Hall technique is used to lock cavity length to our stabilized laser beam.

Monocular gate detection and localization vision pipeline for autonomous drone racing with adaptive and condition-aware perception

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Navigating at high speeds, autonomous drone racing calls for localization that produces accurate pose estimations at such speeds for path planning. This project develops a monocular perception pipeline for reliable pose estimation through gate detection with the onboard compute constraints of an A2RL racing drone. The pipeline combines a segmentation model (SAM/knowledge distilled segmenter), a corner detector (convolutional neural network/QuAdGate line segment detector), and a Perspective-n-Point solver with a Kalman filter. This was tested against simulated images on Jetson hardware and a camera stream showing the gate approach. Across many pipeline configurations, gate detection mainly caused inaccuracies, with the best combination reaching below 40 pixels mean corner error. While testing on the camera stream, the four-corner PnP solver exposed specific failures such as an overfitted model, tracker drift, and a three corner pose ambiguity. This solver has a disambiguator that filters out candidates drastically out of range from its prior predicted position. Building on these findings and the recent work of using reinforcement learning to condition parameters using visual features over fixed parameters, future work may explore an image-based policy for adapting the pipeline's gate detection and pose estimation parameters to the changing racing conditions in real time.

SINDy-LLM: Large language model-augmented framework for the sparse identification of nonlinear dynamics

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Obtaining the equations that model physical phenomena has long been an important but difficult task in science and engineering. Sparse Identification of Nonlinear Dynamics (SINDy) is a powerful data-driven method for discovering these governing equations; however, effective use often requires deep domain knowledge and coordination across specialized tools. In this project, we introduce SINDy-LLM, an agentic, tool-augmented framework for LLM-assisted equation discovery. SINDy-LLM combines callable scientific tools—SINDy variants, denoising, skeleton fitting, and other algorithms—with

Retrieval-Augmented Generation (RAG) and a QLoRA (Quantized Low-Rank Adaptation) fine-tuning pipeline for teaching the model scientific workflow behavior. It is evaluated on both canonical and nonlinear benchmark data systems using symbolic accuracy, term-level F1 (term accuracy), and normalized mean squared error (NMSE).

Neural ODE across the cylinder wake bifurcation

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This work asks whether one data-driven reduced model can represent the two-dimensional cylinder wake on both sides of its primary Hopf bifurcation. The dataset contains 34 trajectories spanning 17 Reynolds numbers from 30 to 160. Across this sweep, the same learned vector field must reproduce decay toward the steady wake below onset and growth toward a stable limit cycle above it. Seventeen independently trained neural ordinary differential equations reproduce trajectories but give uneven estimates of the fixed-point growth rate. A single parameter-conditioned network instead learns the Reynolds-number dependence from the pooled dataset. In its best holdout configuration, the shared model reduces mean growth-rate error from 26.7% to 5.2% over $48 \leq Re \leq 90$, reaches 2.2% error at held-out $Re = 51$ and 5.2% at held-out $Re = 73$, and locates the measured critical Reynolds number, $Re_c = 44.2$, within 1.9%. These results show that parameter sharing can replace a collection of local models with one compact model that interpolates across the bifurcation.

Sparse sensing of fluid–structure interaction dynamics using neural operators

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Sparse-sensor reconstruction of fluid–structure interaction loads could reduce the instrumentation required for aerospace testing and enable continuous structural-load monitoring. This work investigates neural operators as virtual sensors for estimating gust-induced wing-root bending-moment histories from a small number of accelerometer measurements. The study uses an open experimental dataset containing hundreds of wind-tunnel gust encounters performed on several flexible-wing configurations under different operating and excitation conditions. Generalization is assessed using a leave-one-wing-out protocol, in which all gust-response measurements from the test structure are excluded from model training and selection. Baseline regularized linear models have been implemented to establish a benchmark for structural-load reconstruction, and neural operator architectures are developed as the primary modeling approach to assess the ability of data-driven methods to recover structural loads from sparse measurements. The project further investigates temporal encoding, causal estimation, and conditioning on structural properties to improve robustness and enable online load estimation. The causal formulation constructs a continuous load estimate using only measurements available up to the current time, enabling its interpretation as an online virtual sensor. The established evaluation framework will assess robustness across wing configurations and gust conditions, with particular attention to structural transfer, low-amplitude excitation, and generalization to unseen configurations.

Developing a reusable, low-cost microfluidic device to investigate freezing fluid infiltration in porous media

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Modeling the infiltration of freezing fluid in porous media plays an important role in diverse processes such as snow and permafrost hydrology, cryopreservation, and the design and manufacturing of advanced materials. Investigating this behavior allows for the understanding of frost heave, polar ice formation, and the mechanisms for ice nucleation and how ice growth affects the flow patterns of a liquid. Due to the natural opacity of porous media, a transparent 2D porous micromodel is needed to simplify flow imaging. To create a low-cost, reusable, and precise model, we investigated laser cutting and resin printing methods for fabrication. These methods are lower-cost and more accessible than the photolithography methods that are currently used for micromodel production. We identified a combination of 3D resin printing (stereolithography) and acrylic bonding as the most robust method to

produce a precise and transparent micromodel. Using an experimental setup with a cold plate, UV lights, and a fluorescein solution, we imaged the flow in the unsaturated micromodel under subfreezing conditions. We employ binary image analysis to track the water and ice distribution in the micromodel. By systematically varying the injection rate and particle size, we aim to identify the parameters controlling the resulting flow pattern.

Effects of dimensionality and forcing conditions on vortex formation and interactions

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Vortex dipoles and vortex rings are coherent flow structures that form in two-dimensional and three-dimensional flows and can interact through behaviors such as leapfrogging and merging. Although vortex dipoles are often treated as two-dimensional analogues of vortex rings, the effects of dimensionality on their formation and interactions are not fully understood. This project uses numerical simulations to investigate how forcing conditions influence isolated vortices and periodically generated vortex trains. Localized body forcing was used to generate vortex dipoles, and numerical methods were developed to identify the leading vortices, separate them from trailing vorticity, and track their motion. Short forcing durations produced compact dipoles whose motion agreed closely with an idealized point vortex model prediction. Longer forcing durations produced increasingly prominent trailing vorticity and reduced the rate at which circulation accumulated in the leading vortex. Higher Reynolds numbers reduced the loss of circulation caused by viscosity. Dipole trains exhibited leapfrogging at all forcing frequencies examined, indicating that more widely spaced vortices should be studied to identify transitions between interaction regimes. Future work will extend this research to three-dimensional vortex rings and ring trains to determine which behaviors are preserved and which differ across dimensionality.