Research Statement

Numerical methods, solvers and software for coupled problems

Summary

My aim is predictive, geometrically resolved simulation of microstructured systems: trabecular networks in the optic nerve, the leaflets of a heart valve, rough rock joints under confining stress, the membrane of an industrial pump. In all of them the geometry comes from measurement rather than from a designer, the interfaces move and touch, and the quantity of interest depends on contact and coupling that homogenised or partially resolved models average away. Reaching that takes three things at once: discretizations that tolerate interfaces no mesh resolves exactly, solvers whose cost stays nearly linear and whose implementation is shaped for the machine it runs on, and a route from an image to a trustworthy simulation with a quantified statement of what remains uncertain. High-performance computing, multiphysics modelling and learned components are means to that end rather than separate agendas.

Two of the three are my record: the coupling and discretization machinery, and the solvers and software that make it run at scale on GPU supercomputers. The third, recovering the mechanical state a simulation needs from images, is the direction I propose to open; nothing of it is yet in my record, and I keep that distinction explicit throughout.

Completed work

Coupling across non-matching discretizations. Transferring fields between independently generated and independently distributed meshes requires L^2-projections whose assembly must intersect every pair of overlapping elements across processes. With Rolf Krause I developed a parallel algorithm combining geometric search, automatic load balancing and the assembly of the discrete projection operators, as the main contributor to the method and the software (*SIAM J. Sci. Comput.*, 2016). This made mortar-type coupling usable at scale, and it underpins later discretizations with dual Lagrange multipliers for flow in fractured porous media (*J. Comput. Phys.*, 2021), verified against a community benchmark (*Adv. Water Resour.*, 2021), and contact between rough rock surfaces (*Int. J. Rock Mech. Min. Sci.*, 2020).

Structure preservation and geometry. Embedded and immersed methods remove the meshing difficulty but raise the question of what they conserve. We showed that embedded discretizations based on dual Lagrange multipliers within a continuous Galerkin framework are locally conservative (*BIT Numer. Math.*, 2025), and parametric finite elements with smooth bijective mappings represent complex domains on coarse curved meshes while controlling the geometry-related error (*BIT Numer. Math.*, 2017).

Fluid–structure–contact interaction. Building on variational transfer, we formulated an immersed method for fluid–structure interaction (*J. Comput. Phys.*, 2019) and extended it to contact between immersed hyperelastic structures and rigid boundaries (*DD28*, 2026). This enabled fully coupled simulations of bioprosthetic aortic valves with leaflet contact (*EP Europace*, 2021) and, with an industrial partner, of liquid diaphragm pumps.

Solvers and high-performance computing. Contact problems are constrained optimization problems: non-smooth, and at high resolution limited by memory and runtime. I developed a matrix-free multigrid augmented Lagrangian method for obstacle problems in elasticity, including its mixed-precision implementation, with colleagues contributing to the investigation and parts of the design; it attains mesh-independent convergence and solves problems with more than 600 million degrees of freedom on a single NVIDIA GH200 GPU (submitted, 2026). Related work covers space-time multilevel Monte Carlo for cardiac electrophysiology (*J. Comput. Phys.*, 2021), a scalable sampler of Gaussian random fields solving a reaction–diffusion SPDE on embedded meshes, developed with Lawrence Livermore National Laboratory (*Numer. Linear Algebra Appl.*, 2018), large-scale phase-field fracture propagation (*CCF Trans. HPC*, 2021), a matrix-free solver for polarized radiative transfer with more than a billion

unknowns (*J. Comput. Phys.*, 2023), and a distributed sort on hardware-supported MPI collectives, 2.6 times faster than the state of the art on 9,216 cores (*J. Parallel Distrib. Comput.*, 2024).

Software. I lead three open-source libraries: Moonolith (parallel intersection detection, load balancing and variational transfer), Utopia (parallel non-linear, constrained and multilevel solvers) and SFEM (matrix-free and semi-structured finite element operators on GPUs, designed for mixed precision from the start). They are used by partners at ETH Zurich, the University of Bern, HSLU, USI and Lawrence Livermore National Laboratory, and I contribute to MFEM.

Research programme

1. Geometrically resolved discretizations for non-smooth and moving interfaces. Contact, delamination and immersed structures lead to variational inequalities and to constraints posed on surfaces that no mesh resolves exactly. I will develop hybrid fitted and unfitted discretizations with Lagrange multipliers for interfaces carrying cohesive and frictional laws, and study their stability and conservation as we did for embedded methods. The questions I want to answer are how to keep the multiplier spaces stable on geometries taken from imaging, and how to separate geometric error from discretization error in practice.

2. Hardware-aware solvers for constrained problems at extreme scale. The resulting problems are constrained optimization problems whose conditioning degrades with mesh size, penalty parameters and material contrast. I will extend matrix-free multigrid augmented Lagrangian methods and substructured contact solvers to frictional and cohesive interfaces and to self-contact, and co-design them with the hardware: matrix-free and semi-structured operators, mixed precision, lossy-compressed representations and symbolic code generation. The question that interests me is how much accuracy can be traded for speed before robustness is lost, and how to decide that in advance rather than after a failed run.

3. Forward and inverse: recovering mechanical state from images. This direction I am opening rather than continuing. Images give geometry but not state: contact regions, prestress, interface stiffness and material parameters are unknown. I will formulate their recovery as inverse problems constrained by the models above, using high-fidelity simulation to generate training data and learned components to propose the hidden state, with the numerical model checking and correcting what they propose and the uncertainty propagated by multilevel sampling. The target cases are the ones that motivate the whole programme: optic nerve trabeculae and valve leaflets on the biomedical side, pumps and fractured rock on the industrial one.

Funding and supervision

Co-principal investigator of a Swiss National Science Foundation project on immersed methods for fluid–structure–contact interaction (754,364 CHF), leading its USI part as principal investigator; principal investigator of the PASC project XSES-FSI (461,000 CHF); a USI institutional grant; co-principal investigator of the PASC project FraNetG with ETH Zurich. I hold supercomputing allocations at CSCS and at KAUST. I have mentored one postdoctoral researcher and one doctoral student with a second in progress, and supervised eleven master's and bachelor's theses.