Frontiers on Geometric Design, Physical Simulation and Their Integration

Organizers: Falai Chen, Xiaohong Jia

Tianyuan Mathematics Research Center

Kunming, Yunnan Province

July 20–26, 2025

Schedule

July 20 (Registration)

July 21			
Time	Title	Speaker	Chair
08:50-09:00	Opening Address	Falai Chen	Xiaohong Jia
09:00-09:45	Learning-Friendly 3D Modeling: CSG-Stump, ExtrudeNet and Beyond	Jianmin Zheng	Falai Chen
09:45-10:15	Tea Break		
10:15-10:45	Design-through-analysis: recent development	Xin Li	Liyong Shen
10:45-11:15	Constructing multiscale shape functions for seamless CAD/CAE integration without meshing	Ming Li	Liyong Shen
11:15-14:30	Lunch Break		
14:30-15:15	TPMS based Metamaterials: Theory and Design	Ligang Liu	Ron Goldman
15:15-15:45	Tea Break		
15:45-16:15	Topology understanding and topology control in geometric design	Hongwei Lin	Dongming Yan
16:15-16:45	Feature-preserving techniques for geometric computation	Shiqing Xin	Dongming Yan

July 22			
Time	Title	Speaker	Chair
09:00-09:45	Quantum Trigonometric Splines	Ron Goldman	Jianmin Zheng
09:45-10:15	Tea Break		
10:15-10:45	Geometric design and process for CAM	Liyong Shen	Chunming Yuan
10:45-11:15	Generalized Bézier volumes over simple convex polyhedra	Chongyang Deng	Chunming Yuan
11:15-14:30	Lunch Break		
14:30-15:15	Polynomial Preserving Recovery for Gradient and Hessian	Zhimin Zhang	Ligang Liu
15:15-15:45	Tea Break		
15:45-16:15	Surface parmeterization by means of boundary informed dynamic graph convolutional networks	Angelos Mantzaflaris	Xin Li
16:15-16:45	Complex shape modeling and analysis using TCB-splines and Bézier techniques	Juan Cao	Xin Li
16:45-17:15	Tool path planning method for parametric surfaces based on piecewise Coons stream function reconstruction on hierarchical T-meshes	Yingshi Li	Xin Li

July 23			
Time	Title	Speaker	Chair
09:00-09:45	On Implementation and Integration with CAD of High-Order Unfitted Finite Element Methods	Linbo Zhang	Zhimin Zhang
09:45-10:15	Tea Break		
10:15-11:45	PANEL-The Next Generation of CAD, CAE and Their Integration		
11:45-14:30	Lunch Break		
14:30-17:00	Free Discussion		

July 24			
Time	Title	Speaker	Chair
09:00-09:45	A Neural Network Approach for Intelligent Unstructured Mesh Generation: A Preliminary Study	Laiping Zhang	Linbo Zhang
09:45-10:15	Tea Break		
10:15-10:45	A Cartesian grid method for nonhomogeneous elliptic interface problems on unbounded domains	Wenjun Ying	Tao Cui
10:45-11:15	CAD-CAE: boundary integral equation method	Tao Yin	
11:15-14:30	Lunch Break		
14:30-15:15	Challenges in the Numerical Analysis of Geometric Flows and Moving Boundary/Interface Problems	Buyang Li	Ron Goldman
15:15-15:45	Tea Break		
15:45-16:15	Isogeometric analysis based on subdivision	Hongmei Kang	Shiqing Xin
16:15-16:45	Volumetric multi-patch parameterizations of complex domains for isogeometric analysis using MAT-based decomposition	Maodong Pan	

July 25			
Time	Title	Speaker	Chair
09:00-09:30	Differentiable microstructures design and its multiscale extension	Xiaoya Zhai	Mingyang Zhao
09:30-10:00	Boolean operation for CAD models using a hybrid representation	Yingyu Yang	
10:00-10:30	Multi-surface developable approximation of B-Rep models under global error control	Kexin Meng	
10:30-11:30	Group Discussion of Young Researchers		
11:30-14:30	Lunch Break		
14:30-17:00	Free Discussion		
July 26 (Departure)			

Plenary Talks (In alphabetical order by last name):

Ron Goldman, Rice University, US
Buyang Li, The Hong Kong Polytechnic University
Ligang Liu, University of Science and Technology of China
Laiping Zhang, Sichuan University
Linbo Zhang, Academy of Mathematics and Systems Science, CAS
Zhimin Zhang, Wayne State University, US
Jianmin Zheng, Nanyang Technological University, Singapore

Participants (In alphabetical order by last name):

Ying Cai, University of Science and Technology of China
Juan Cao, Xiamen University
Falai Chen, University of Science and Technology of China
Tao Cui, Academy of Mathematics and Systems Science, CAS
Chongyang Deng, Hangzhou Dianzi University
Bingru Huang, University of Science and Technology of China
Xin Jiang, Beihang University
Xiaohong Jia, Academy of Mathematics and Systems Science, CAS
Hongmei Kang, Soochow University
Ming Li, Zhejiang University
Hongwei Lin, Zhejiang University
Xin Li, University of Science and Technology of China
Angelos Mantzaflaris, Inria at Université Côte d'Azur
Maodong Pan, Nanjing University of Aeronautics and Astronautics
Liyong Shen, University of Chinese Academy of Sciences
Weihua Tong, University of Science and Technology of China
Xuhui Wang, Hohai University
Meng Wu, Nanjing University of Science and Technology
Shiqing Xin, Shandong University
Dongming Yan, Institute of Automation, CAS
Peng Yang, University of Electronic Science and Technology of China
Wenjun Ying, Shanghai Jiao Tong University
Tao Yin, Academy of Mathematics and Systems Science, CAS
Chunming Yuan, Academy of Mathematics and Systems Science, CAS
Xiaoya Zhai, University of Science and Technology of China
Baiju Zhang, Yunnan University

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Abstracts

Learning-Friendly 3D Modeling: CSG-Stump, ExtrudeNet and Beyond

Jianmin Zheng
Nanyang Technological University

Abstracts: Creating structured 3D models of real-world objects is crucial for bridging the physical and digital worlds, enabling applications across design, manufacturing, robotics, and virtual environments. This process, however, remains challenging due to the complexity of real-world shapes and the need for efficient and interpretable modeling techniques. This talk begins with a brief analysis of key technical components in 3D modeling for real-world applications and then introduces several recent research efforts aimed at high-level shape representation and efficient 3D reconstruction. Key highlights include CSG-Stump, a learning-friendly representation based on CSG that encodes the composition of modeling primitives in a structured and regular fashion, and ExtrudeNet, a network that reverse-engineers the sketch-and-extrude modeling process in an unsupervised manner. I will also introduce a differentiable approach to convex decomposition that facilitates shape parsing and convex primitive generation. These methods offer new pathways for understanding, reconstructing, and repurposing 3D shapes from point clouds, multi-view images, and implicit representations.

Design-through-analysis: recent development

Xin Li
University of Science and Technology of China

Abstracts: This talk will introduce our recent development in design-through-analysis, which includes two main parts: spline surface reconstruction from different input and isogeometric analysis solver for interface PDE. In the first work, we provides several algorithms to reconstruct spline surface with arbitrary topology from 1) a bounded regions with boundary information; 2) triangle meshes; 3)the surface from topology optimization. In the second work, we will introduce a robust and stable IGA solver for interface problem with optimal convergence rates. The solver will maintain all the spline basis unchanged and add some new enrichment basis which can integrate with CAD easily.

Constructing multiscale shape functions for seamless CAD/CAE integration without meshing

Ming Li
Zhejiang University

Abstracts: Seamless CAD / CAE integration aims to build a smooth transition between CAD and CAE for structure design, simulation and optimization, and would significantly accelerate the design cycle and improve the design quality. However, seamless CAD/CAE integration faces fundamental challenges on such model preparations as cleanup, simplification, meshing, and feature-based modifications. In this talk, we introduce our recent progress on embedded FE-based analysis on coarse regular background grid via constructing multiscale shape functions.
The accuracy, efficiency and stability of the approach is analyzed and tested on various examples. A concept of xVoxel for feature-based simulation and optimization is also introduced.

TPMS based Metamaterials: Theory and Design

Ligang Liu
University of Science and Technology of China

Abstracts: Porous shell lattice structures are commonly adopted in designing metamaterials. Shell structures based on Triply Periodic Minimal Surfaces (TPMS) have gained widespread recognition due to their significant heat transfer (e.g., enhanced surface area) and diverse mechanical properties (e.g., structural stability), making them highly valuable in numerous applications. But, why TPMS based structures have such nice physical properties is still an open problem.

We propose a novel metric, called asymptotic directional stiffness (ADS), which quantifies the influence of the geometry of middle surface to the effective stiffness of shell lattice. We perform an asymptotic analysis of the structures and derive the convergence theorem, which allows us to establish an upper bound for ADS and identify the necessary and sufficient conditions for achieving this bound. Therefore, we present the first rigorous theoretical explanation for the exceptional bulk modulus observed in the TPMS shell lattices. To improve the ADS of a general periodic surface, we propose a discretization scheme on triangular meshes for evaluating and optimizing ADS. Moreover, we present an efficient topology and geometry optimization of TPMS structures, which can be represented, analyzed, optimized and stored directly using functions.

Topology understanding and topology control in geometric design

Hongwei Lin
Zhejiang University

Abstracts: Persistent homology, represented by persistence diagrams, is a fundamental tool in computational topology. By integrating this approach into geometric design, we empower traditional geometric design methods with topological control capabilities, significantly enhancing algorithm robustness. In reverse engineering, persistence diagrams are first employed to extract critical topological features from point clouds, enabling topological understanding. For example, we can determine the number of connected components in a given point cloud or identify whether a component represents a closed geometric object before reconstruction. Leveraging this topological information, along with topological representatives as initial reconstruction templates, our method can reconstruct intersecting curves and multiple geometric objects simultaneously while vastly improving the robustness of reconstruction algorithms. Additionally, by designing objective functions on persistence diagrams and applying optimization techniques, we can precisely control the topological structure of reconstructed curves and surfaces.

Feature-preserving techniques for geometric computation

Shiqing Xin
Shandong University

Abstracts: Preserving geometric features is critical for maintaining shape fidelity in various computational geometry tasks. In this talk, I will present a set of systematic feature-preserving techniques developed for core operations such as mesh simplification, shape offsetting, and medial axis computation. These techniques are designed to retain sharp edges, ridges, and other salient features that are often lost during geometric processing. I will discuss the underlying principles, key algorithmic ideas, and practical challenges associated with each scenario. The effectiveness of these techniques is demonstrated through representative examples and quantitative comparisons.

Quantum Trigonometric Splines

Ron Goldman
Rice University

Abstracts: The goal of this talk is to present a quantum generalization of trigonometric B-splines. We begin with a brief introduction to the quantum calculus, including quantum exponential and quantum trigonometric functions along with formulas for quantum differentiation and quantum integration. Using these quantum formulas along with non-polynomial divided differences, we define quantum trigonometric B-splines. Then we present quantum recurrence relations, differentiation formulas, Marsden identities, and integral representations of divided differences for quantum trigonometric B-splines, and we compare these quantum formulas to the corresponding standard formulas for classical B-splines.

Geometric design and process for CAM

Liyong Shen
University of Chinese Academy of Sciences

Abstracts: The engineering production chain from digital design to numerical control manufacturing is lengthy and involves a wide range of research fields, including several core common mathematical theories and methods such as computational geometry, geometric design and analysis, graphics data processing, path planning and motion control, and geometric machine learning. Among these, the establishment, analysis, and solution of mathematical models are the most critical processes. This talk will introduce the academic and engineering progress made by our research group in the digital intelligent machining process.

Generalized Bézier volumes over simple convex polyhedra

Chongyang Deng
Hangzhou Dianzi University

Abstracts: Building upon Varady et al.'s (2016) polygonal Generalized Bézier (GB) patch, we present a novel polyhedral volumetric modeling technique: the Generalized Bézier (GB) volume. These GB volumes are constructed over simple convex polyhedral domains using generalized barycentric coordinates (GBCs), featuring control nets that naturally extend the tensor-product Bézier volume paradigm. Our methodology involves two key innovations: first, we generalize Bézier surfaces to prismatic parameter domains, creating tensor-product GB volumes; second, we establish a mapping between simple polyhedral domains and prismatic domains through GBCs, enabling GB volume construction on arbitrary simple polyhedra. By adjusting shape parameters and weighting factors, our GB volumes achieve multi-level geometric continuity (up to G^2) with boundary solids. This approach demonstrates potential for applications including volumetric hole-filling in solid modeling and isogeometric analysis (IGA).

Polynomial Preserving Recovery for Gradient and Hessian

Zhimin Zhang
Wayne State University

Abstracts: Post-processing techniques are crucial in scientific and engineering computation. One such technique, Superconvergent Patch Recovery (SPR), proposed by Zienkiewicz-Zhu in 1992, has been widely used in finite element commercial software packages such as Abaqus, ANSYS, Diffpack. Another technique, Polynomial Preserving Recovery (PPR), has been adopted by COMSOL Multiphysics since 2008. In this talk, I will survey the PPR method and discuss its development for obtaining the Hessian matrix (second derivatives) from the computed data.

Surface parmeterization by means of boundary informed dynamic graph convolutional networks

Angelos Mantzaflaris
Inria at Université Côte d'Azur

Abstracts: Surface reconstruction from scattered point clouds is the process of generating surfaces from unstructured data configurations retrieved using an acquisition device such as a laser scanner. One key step in the spline surface reconstruction process is the parameterization of the points, that is, the construction of a proper mapping of the 3D point cloud to a planar domain that preserves surface boundary and interior points. Despite achieving a remarkable progress, existing heuristics for generating a suitable parameterization face challenges related to the accuracy, the robustness with respect to noise, and the computational efficiency of the results. In this talk, we present a Boundary Informed Dynamic Graph Convolutional Network (BIDGCN) characterized by a novel boundary informed input layer, with special focus on applications related to adaptive spline approximation of scattered data. The newly introduced layer propagates given boundary information to the interior of the point cloud, in order to let the input data be suitably processed by successive graph convolutional network layers. We apply our BIDGCN model to the problem of parameterizing three-dimensional unstructured data sets over a planar domain. A selection of numerical examples shows the effectiveness of the proposed approach for adaptive spline fitting with (truncated) hierarchical B-spline constructions.

Complex shape modeling and analysis using TCB-splines and Bézier techniques

Juan Cao
Xiamen University

Abstracts: Traditional and emerging spline technologies provide high-fidelity representations of analysis models and have been widely adopted in isogeometric analysis and high-order finite element methods. By reducing geometric errors and improving numerical accuracy, they play a key role in enabling integrated design and analysis. This talk presents our group’s recent progress on TCB-splines and Bézier techniques, with a focus on modeling complex geometries and achieving high-precision representation of intricate boundaries and interfaces for analysis. We also showcase their preliminary applications in practical engineering problems, including thin-shell analysis, shape optimization, and multi-material large deformation simulations.

Tool path planning method for parametric surfaces based on piecewise Coons stream function reconstruction on hierarchical T-meshes

Yingshi Li
Dalian University of Technology

Abstracts: Vector field-based tool path planning methods have been widely used for freeform surface machining, as they can effectively capture preferred feed directions that reflect the designers' machining intent. Among these methods, the stream function reconstruction algorithm stands out for its capability to generate tool paths with high machining efficiency. During the reconstruction process, there are two key problems that remain to be solved: controlling scallop height between adjacent paths to reduce redundant machining, and addressing the computational inefficiencies of the commonly used tensor product B-spline functions, which lack local refinement properties. To overcome these limitations, this paper proposes a novel global tool path planning method based on piecewise Coons stream function reconstruction on adaptively hierarchical T-meshes. This approach introduces an optimal stream function reconstruction model that integrates three optimization objectives: tool path alignment with the vector field, uniform distribution of scallop height between adjacent paths, and smoothness of the tool paths. Subsequently, an adaptively piecewise Coons function reconstruction algorithm is developed, utilizing the Coons interpolation for precise and efficient tool path generation. Experimental results validate the effectiveness of the proposed method.

On Implementation and Integration with CAD of High-Order Unfitted Finite Element Methods

Linbo Zhang
Academy of Mathematics and Systems Science, Chinese Academy of Sciences

Abstracts: Unfitted finite element methods (UFEM), in which the mesh is not required to fit the geometry of the computational domain, have attractive advantages in dealing with problems involving complex, evolving, changing or curved geometries, but efficient implementation of the state of the art UFEM algorithms, especially the high-order ones, still remains a challenging problem with many unresolved issues. In this talk I will present our progress on extending our parallel adaptive finite element toolbox Parallel Hierarchical Grid (PHG, http://lsec.cc.ac.cn/phg/index_en.htm) to support developing parallel high-order UFEM programs, and discuss issues related to handling general CAD models.

A Neural Network Approach for Intelligent Unstructured Mesh Generation: A Preliminary Study

Laiping Zhang
Sichuan University

Abstracts: Mesh generation is a critical initial step in numerical simulation, where its efficiency and quality directly govern the overall performance and accuracy of the simulation process. Developing highly efficient and automated methods for generating high-quality unstructured meshes remains a significant challenge. Motivated by the widespread advances in Artificial Intelligence (AI) and Artificial Neural Networks (ANNs), this work explores leveraging AI to extract valuable patterns and features from extensive accumulated mesh data. This approach promises to reduce manual effort, enhance efficiency, lower costs, and advance numerical simulation capabilities.

This study aims to establish a neural network-based framework for efficient unstructured mesh generation. Key objectives include: (1) constructing and automatically extracting unstructured mesh sample datasets; (2) developing and training specialized ANN models for feature extraction across diverse data types; and (3) creating efficient methods for isotropic and anisotropic mesh generation. Utilizing pre-processed and augmented sample data, we establish and train ANN models to accurately predict key parameters within the Advancing Front Method (AFM) and Advancing Layer Method (ALM). By integrating these pre-trained models, we upgrade traditional AFM/ALM workflows, replacing computationally intensive steps. This hybrid approach achieves a 50% increase in the overall efficiency of anisotropic hybrid mesh generation.

A Cartesian grid method for nonhomogeneous elliptic interface problems on unbounded domains

Wenjun Ying
Shanghai Jiao Tong University

Abstracts: Cartesian grid methods may be an approach for integration of geometric design and physical simulation. We will present a Cartesian grid based fast and accurate method for indirectly evaluating boundary and volume integrals in a boundary-volume integral approach for nonhomogeneous elliptic interface problems on unbounded domains. The indirect calculation is done by solving equivalent but simple interface problems. We accelerate the computation by introducing an intermediate, transitional circle or sphere and taking advantages of super-convergent numerical quadrature or series expansion on circles/spheres. We first map the boundary or volume integral on the irregular boundary or domain to the intermediate circle/sphere; then evaluate the boundary integral on the intermediate circle/sphere to get boundary conditions for the simple interface problem. We will also show numerical results of examples in both two and three space dimensions.

CAD-CAE: boundary integral equation method

Tao Yin
Academy of Mathematics and Systems Science, Chinese Academy of Sciences

Abstracts: This talk will present some recent progresses on the fast and high-order boundary integral equation solvers for solving the frequency-domain wave scattering problems. Some regularization techniques and the associated theoretical analysis of the singular integral operators are developed to reduce the singular integrals to combinations of weakly-singular integral operators and surface differential operators whose numerical evaluations can be achieved by means of a Chebyshev-based rectangular-polar solver. This provides a novel CAD-CAE approach which can avoid the evaluation of mesh and can efficiently treat different complex CAD geometries. Numerical examples will be presented to show the accuracy and efficiency of the proposed solvers.

Challenges in the Numerical Analysis of Geometric Flows and Moving Boundary/Interface Problems

Buyang Li
The Hong Kong Polytechnic University

Abstracts: We discuss some challenges in the numerical analysis of geometric flows and free boundary problems in fluid dynamics. Then we present recent advances in the numerical analysis and algorithmic design for solving these complex and evolving systems. Topics include the convergence of finite element methods for mean curvature flow, the convergence of interface tracking methods for two-phase flows, and the design of artificial tangential motions to improve mesh quality in computing evolving surfaces.

Isogeometric analysis based on subdivision

Hongmei Kang
Soochow University

Abstracts: Subdivision technology can provide a globally smooth representation for complex geometric models and has become one of the commonly used geometric representation methods in isogeometric analysis for dealing with complex computational domains in recent years. Subdivision surfaces can be regarded as the extension of box splines and B-splines to complex topological geometric models. The challenges of isogeometric analysis based on subdivision lie in the reduced analysis accuracy at extraordianry points and the complicated computations. In this report, I will systematically introduce some research progress and future considerations in isogeometric analysis based on subdivision, including the construction of subdivision surfaces with optimal convergence rates, a novel framework for adaptive isogeometric analysis, superconvergent isogeometric collocation methods, and their applications in the field of topology optimization.

Volumetric multi-patch parameterizations of complex domains for isogeometric analysis using MAT-based decomposition

Maodong Pan
Nanjing University of Aeronautics and Astronautics

Abstracts: Constructing volumetric spline parameterizations for physical domains from their given boundary representations is a crucial step in isogeometric analysis. However, this task remains challenging, particularly for complex geometries. This work presents a novel multi-patch volumetric parameterization method specifically designed for complex domains with arbitrary topologies. The new method unfolds in two main stages: First, the input complex domain is decomposed into structurally meaningful patches using information from its medial axis transform (MAT). This process includes simplifying the extracted MAT, refining the curve skeleton, segmenting the MAT, optimizing boundary cuts, and performing domain decomposition. Second, constructing C0 multi-patch parameterizations of the physical domain, which involves establishing boundary correspondence, ensuring C0 continuity between adjacent surfaces, and computing high-quality single-patch parameterizations. Various tested examples and the comparisons with a state-of-the-art approach demonstrate the capability and superiority of the proposed method.

Differentiable microstructures design and its multiscale extension

Xiaoya Zhai
University of Science and Technology of China

Abstracts: The design of microstructures plays a pivotal role in bridging material architecture with targeted physical properties, enabling next-generation engineering systems across aerospace, biomedical, and mechanical domains. This talk introduces a differentiable framework for microstructure design that integrates physical simulation, geometry representation, and gradient-based optimization into a unified pipeline. We further extend this framework to support multiscale modeling, where designed microstructures are seamlessly embedded into macroscopic structures with spatially varying properties. The presentation highlights key algorithmic components, demonstrates performance on billion-degree-of-freedom problems, and outlines future directions in coupling learning-based priors and experimental validation.

Boolean operation for CAD models using a hybrid representation

Yingyu Yang
Academy of mathematics and systems science, Chinese academy of sciences

Abstracts: Boolean operations for Boundary Representation (B-Rep) models are among the most commonly used functions in Computer Aided Design (CAD) systems. They are also one of the most delicate soft modules, with challenges arising from complex algorithmic flows and efficiency and accuracy issues, especially in extreme cases. Common issues encountered in processing complex models include low efficiency, missing results, and non-watertightness. In this report, we present a novel algorithm for efficient and accurate Boolean operations on B-Rep models. This is achieved by establishing a bijective mapping between B-Rep models and the corresponding triangle meshes with controllable approximation error, thus mapping B-Rep Boolean operations to mesh Boolean operations. By using conservative intersection detection on the mesh to locate all surface intersection curves and carefully handling degeneration and topology errors, we ensure that the results are consistently watertight and correct. We demonstrate the superior efficiency of the proposed method using the open-source geometry engine OCCT, the commercial engine ACIS, and the commercial software Rhino as benchmarks.

Multi-surface developable approximation of B-Rep models under global error control

Kexin Meng
Academy of mathematics and systems science, Chinese academy of sciences

Abstracts: In computer-aided design (CAD), approximation by developable surfaces of 3D shapes has emerged as a significant research focus, due to their exceptional geometric properties and broad practical applications. However, current studies on developable approximation of parametric surfaces focus only on individual surfaces, usually constrained to rectangular parametric domains. These approaches are unsuitable for handling multiple parametric surfaces with complex inner/outer boundaries in B-Rep models. We propose a novel piecewise developable approximation method for B-Rep models. We first partition the input surfaces via greedy region-growing segmentation based on local geometric properties at each point, where adjacent regions from different surfaces may segment into a common patch. Each patch is then approximated by a developable surface (plane, cylinder, cone, or tangent surface) through directrix curve fitting. Global error control is achieved via adaptive patch subdivision. Finally, the approximating developable surfaces are trimmed according to both the original surface boundaries and segmentation lines. Empirical results demonstrate that our method generates fewer or higher-quality developable patches under identical tolerance constraints compared to existing approaches, validating the effectiveness and superiority of our method, demonstrating broad applicability to multiple parametric surfaces with complex boundaries.