Topology Optimization and Isogeometric Analysis

September 11 - 13, 2023

Book of Abstracts

Program

Monday, September 11, 2023

13:45 – 14:00 Opening

14:00 – 14:30 Peter Gangl (RICAM)
An Introduction to Topology Optimization

14:30 – 15:15 Stefan Takacs (JKU Linz)
An Introduction to Isogeometric Analysis

15:15 – 15:45 Coffee break

15:45 – 16:15 Thomas Takacs (RICAM)
Geometric Challenges in Isogeometric Analysis

16:15 – 17:00 Mario Kapl (Carinthia University of Applied Sciences)
C^1 smooth isogeometric spline spaces for trilinearly parameterized multi-patch volumes

17:00 – 17:45 Andrea Bressan (IMATI CNR)
A dirty trick

Tuesday, September 12, 2023

08:30 – 09:15 Emad Shakur (RICAM)
Isogeometric analysis for solving topology optimization problems with precise and explicit boundary representation

09:15 – 10:00 Fehmi Cirak (Cambridge University)
Unified geometry and analysis representations for shape and topology optimisation

10:00 – 10:40 Coffee break

10:40 – 11:05 Bert Jüttler (JKU Linz)
Locally linearly independent B-spline bases on adaptively refined hierarchical T-meshes

11:05 – 11:30 Felix Scholz (JKU Linz)
Optimizing isogeometric discretizations using deep neural networks

11:30 – 12:15 Benjamin Marussig (TU Graz)
Immersed Boundary-Conformal Method: An isogeometric discretization for topology optimization?

12:15 – 14:00	Lunch break
14:00 – 14:45	Majd Kosta (Technion) Multi-material stress constrained topology optimization with precise evolving boundaries using IGA
14:45 – 15:30	Michael Wiesheu (TU Darmstadt) Topology Optimization of a Magnetocaloric Refrigeration System with Isogeometric Analysis
15:30 – 16:15	Coffee break
16:15 – 17:00	Hugo Verhelst (TU Delft) Isogeometric Analysis of Wrinkling
19:00	Dinner (Location TBD)

Wednesday, September 13, 2023

09:00 – 09:35	Jan Groselj (University of Ljubljana) C^1 Clough-Tocher splines of higher degrees in a B-spline-like representation
09:35 – 10:10	Marjeta Knez (University of Ljubljana) A family of C^1 Clough-Tocher spline spaces on G0 piecewise quadratic domain partitions
10:10 – 10:45	Coffee break
10:45 – 11:30	Jochen Hinz (EPFL) Spline-based parameterisation techniques
11:30 – 12:15	Ye Ji (TU Delft/Dalian) Analysis-suitable Parameterization Techniques for Isogeometric Analysis

A dirty trick

Andrea Bressan (IMATI CNR)

The simulation of underground water flow is very important for the management of water resources. One of the difficulties is that the phreatic surface, i.e. the boundary between the saturated soil and the dry soil, is unknown. The talk will be a report of empirical experiments in the quest of a isogeometric method based on shape optimization techniques with particular emphasis to the dam problem.

Unified geometry and analysis representations for shape and topology optimisation

Fehmi Cirak (Cambridge University)

Advances in manufacturing technologies, most prominently additive manufacturing or 3d printing, make it possible to fabricate highly optimised products with increased geometric and hierarchical complexity. Computational tools are indispensable in representing and navigating the corresponding vast design spaces. Shape and topology optimisation aim to provide designers with computational tools to interactively explore and find geometries that must satisfy various quantitative and qualitative requirements. This talk will introduce our ongoing work in developing unified structural optimisation tools that combine CAD-compatible geometry representations, multiresolution geometry processing techniques and immersed/embedded finite elements with classical shape and topology optimisation. As example applications, the shape and topology optimisation of solid, shell and lattice-skin structures and their representation as compact parametric CAD models will be discussed.

An Introduction to Topology Optimization

Peter Gangl (RICAM)

Topology optimization methods aim at finding optimal designs of structures while allowing for a change of their topology. Over the past decades, different topology optimization methods have been investigated and used in a wide variety of engineering applications. In this talk, I will give an overview over the most widely used approaches and discuss their advantages and challenges.

C^1 Clough-Tocher splines of higher degrees in a B-spline-like representation

Jan Grošelj (University of Ljubljana)

The Bernstein-Bezier techniques for bivariate polynomials are a convenient tool for construction and analysis of C^1 splines over a triangulation. In this talk we use them to assemble a set of basis functions that span a space of super-smooth C^1 splines of a chosen degree higher than three over a Clough-Tocher refined triangulation. The considered splines generalize the classical cubic finite element defined over such a refinement and can be represented in a B-spline-like form.

Spline-Based Parameterisation Techniques

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Isogeometric analysis (IGA) [1] is a variant of the finite element method (FEM) that was conceived in an effort to bridge the gap between the disjoint disciplines of computer aided design (CAD) and FEM. For this, IGA employs NURBS both for the geometrical as well as the numerical aspects of the computational simulation workflow. Hereby, the surface-to-volume (StV) problem $\partial\Omega \to \Omega$ of finding a valid description of the geometry's interior from no more than a (spline / NURBS-based) description of its boundary becomes the IGA analogue of the classical meshing step. As such, the spline-based StV-step has received an increased amount of interest in recent years [2]. Besides providing a nondegenerate map (i.e., one with a strictly positive Jacobian determinant) proficient algorithms furthermore aim for numerically favourable parametric properties, such as orthogonal isolines and homogeneous cell sizes [3].
While substantial advancements have been made, most of them have been restricted to the singlepatch setting, i.e., when Ω can be parameterised from the unit quadrilateral. To expand upon this limitation, this talk proposes a framework for parameterising two- and *two-and-a-half*-dimensional domains that are topologically equivalent to some convex multipatch domain. For this, we adopt the concept of harmonic maps and propose several algorithms for tackling a PDE-based problem formulation that can be effortlessly integrated into a well-developed IGA software suite.
Parametric control is achieved by introducing an appropriate coordinate transformation in the parametric domain $\hat{\Omega}$. We discuss techniques for finding a so-called *control map* $\mathbf{s} : \hat{\Omega} \to \hat{\Omega}$ that induces a coordinate transformation capable of providing maps with boundary orthogonality, cell size homogeneity and various other desired features.
Finally, we discuss how the use of VarMiONs [4], a neural network layout geared towards approximating PDE-problems, can aid in the fast on-the-fly computation of harmonic maps and present first results.

References

[1] Hughes, Thomas JR, John A. Cottrell, and Yuri Bazilevs. "Isogeometric analysis: CAD, finite elements, NURBS, exact geometry and mesh refinement." Computer methods in applied mechanics and engineering 194.39-41 (2005): 4135-4195.

[2] Xu, G., Mourrain, B., Duvigneau, R., & Galligo, A. (2011). Parameterization of computational domain in isogeometric analysis: methods and comparison. Computer Methods in Applied Mechanics and Engineering, 200(23-24), 2021-2031.

[3] Gravesen, J., Evgrafov, A., Nguyen, D. M., & Nørtoft, P. (2014). Planar parametrization in isogeometric analysis. In Mathematical Methods for Curves and Surfaces: 8th International Conference, MMCS 2012, Oslo, Norway, June 28-July 3 2012, Revised Selected Papers 8 (pp. 189-212). Springer Berlin Heidelberg.

[4] Patel, Dhruv, et al. "Variationally mimetic operator networks." arXiv preprint arXiv:2209.12871 (2022).

Analysis-suitable Parameterization Techniques for Isogeometric Analysis

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Abstract

In the field of IsoGeometric Analysis (IGA), the pivotal first step entails creating a high-quality, analysis-suitable domain parameterization derived from the boundary representation of a CAD model. This foundational procedure exerts a substantial influence on downstream operations, including, but not limited to, simulation and structural design optimization. Although algebraic methods like the discrete Coons and Spring patch techniques provide simple and efficient solutions, they often prove insufficient for complex geometric challenges.

In the first part of our talk, we spotlight two types of robust and efficient parameterization methods: the Barrier-type Optimization-based Method (Ji et al. 2021; Ji et al. 2022a) and the PDE-based Elliptic Grid Generation Method (Ji et al. 2023). Our parameterization technique has been successfully applied in real-world industrial application, exemplified by the structured mesh generation of twin-screw compressors. All the methods discussed have been integrated into the Geometry + Simulation Modules (G+Smo) library – an open-source C++ toolkit dedicated to geometric design and isogeometric simulations.

In the second part of our talk, we introduce a bi-level, curvature-based r-adaptive parameterization method aimed at achieving enhanced numerical accuracy without increasing the degrees of freedom (Ji et al. 2022b). The principal feature is utilizing the so-called absolute principal curvature of the IGA solution surfaces to characterize numerical errors. Numerical experiments demonstrate the effectiveness and efficiency of our method.

References

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Ji, Ye, Ying-Ying Yu, Meng-Yun Wang, and Chun-Gang Zhu. 2021. "Constructing high-quality planar NURBS parameterization for isogeometric analysis by adjustment control points and weights." *Journal of Computational and Applied Mathematics* 396:113615.

Locally linearly independent B-spline bases on adaptively refined hierarchical T-meshes

Bert Jüttler (JKU Linz)

joint work with Lisa Groiss and Maodong Pan

Adaptive spline refinement is an essential tool for achieving efficiency in isogeometric analysis. The available constructions for adaptively refined spline spaces include T-splines, hierarchical B-splines (HB-splines), truncated hierarchical B-splines (THB-splines), polynomial splines over hierarchical T-meshes (PHT-splines), and locally refined B-splines (LR B-splines). We investigate methods that ensure the existence of a basis that (1) consists of standard tensor-product B-splines, which (2) form a non-negative partition of unity and (3) are locally linearly independent. The latter condition ensures that only the minimum number of basis functions are active on each element. Previous results in this direction have been obtained by considering LR B-splines within the framework of HB-splines (Bressan and Juettler, 2015, CAGD) and by combining the non-nested support condition (Bressan, 2013, CAGD) with structured mesh refinement of LR B-splines (Patrizi et al., 2020, CMAME). The talk focuses on the combination of LR B-splines with PHT-splines. We present a new mesh refinement algorithm, which ensures that the resulting set of LR-splines possesses the three properties (1-3). The algorithm is extremely simple, since it proceeds by inserting a single split (or mesh line) at each step, which is possibly extended if necessary to the local linear independence property (3). In order to prove the correctness of our approach, we introduce and analyze the standardized local configurations of a mesh. We show that these configurations, which locally capture the topology and connectivity of the mesh, admit only a finite number of configurations. The number of cases is quite large, highlighting the difficulties of ensuring linear independence of LR B-splines. Nevertheless, the analysis of these configurations is sufficient to prove the correctness of our mesh refinement procedure. The main advantage of the new method is that it allows the creation of refined meshes in an adaptive manner, as both the size and shape of the elements can be flexibly adapted to the underlying application.

C^1-smooth isogeometric spline spaces for trilinearly parameterized multi-patch volumes

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On the one hand, multi-patch volumes are required to describe complex volumetric domains, which in general cannot be represented just by one single patch. On the other hand, globally C^1-smooth functions are needed to solve fourth order PDEs, such as the biharmonic equation, the Cahn-Hilliard equation or problems of strain gradient elasticity analysis, via their weak form and a standard Galerkin discretization as mostly applied in isogeometric analysis.

In this talk, we aim at combining both needs by presenting the design of a C^1-smooth isogeometric spline space over trilinearly parameterized multi-patch volumes. At first, we study the case of two patches and generate an explicitly given and locally supported basis for the C^1-smooth isogeometric spline space. Then, we use this result to develop a general framework for the construction of the C^1-smooth space and of an associated basis for any given trilinearly parameterized multi-patch volume. Finally, the method is demonstrated in more detail on the basis of trilinear multi-patch volumes with exactly one inner edge for which we numerically compute the dimension and explore the approximation properties of the C^1-smooth isogemetric spline space.

Joint work with: Katharina Birner and Vito Vitrih.

A family of C^1 Clough-Tocher spline spaces on G^0 piecewise quadratic domain partitions

Marjeta Knez (University of Ljubljana)

Bivariate polynomials of a fixed total degree naturally extend to splines over triangulations. The standard approach is to define these splines over a planar domain with a polygonal boundary that is partitioned by a collection of non-overlapping triangles. The spline function is then expressed locally over every triangle using barycentric coordinates and the Bernstein–Bézier representation. However, in the isogeometric setting, every triangle can be seen as a patch in the physical space, parameterized by a linear geometry mapping, defined by the first two barycentric coordinates, and the triangulation represents a multipatch domain. Replacing the linear geometry mapping by a polynomial mapping of a higher degree gives the curved triangles, where every edge of the curved triangle is parameterized by a polynomial curve. The curved triangles represent building blocks for so called curved triangulations that can be used to cover or approximate with more flexibility the domains with a smooth boundary. In this talk we focus on C^1 smooth splines over a quadratic triangulation where every curved triangle is parameterized by a quadratic geometry mapping. The construction is based on a recently developed theoretical framework ([1]) for the analysis of C^1 smoothness conditions over the common interface of two quadratically parameterized mixed mesh elements. Since we want the construction to be local and independent of the geometry of the triangulation as well as to allows us to use, in the parametric space, the polynomials of not too high degree, we split every curved triangle into three curved micro-triangles by applying the Clough–Tocher refinement and observe the spline space over the refined quadratic triangulation. Following the ideas used in [2], we define the interpolation problem that uniquely defines functions in this space and allows us to compute the basis. Knowing the basis opens the door for using these spline spaces for different approximation problems as well as for solving different PDEs. Some of the numerical results confirming the theoretical findings and the properties of the derived spaces and their bases are presented at the end of the talk.

1. J. Grošelj, M. Kapl, M. Knez, T. Takacs, V. Vitrih: C1-smooth isogeometric spline functions of general degree over planar mixed meshes: The case of two quadratic mesh elements, Applied Mathematics and Computation, 2023, art. 128278.

2. J. Grošelj, M. Knez: Generalized C1 Clough-Tocher splines for CAGD and FEM, Computer methods in applied mechanics and engineering, May 2022, vol. 395, art. 114983.

Multi-material stress constrained topology optimization with precise evolving boundaries using IGA

Majd Kosta (Technion)

In a typical engineering design process, Computer aided design models (CAD) are utilized as input for numerical simulation using finite element analysis (FEA). A gap between CAD and FEA representations motivated the initial work on iso geometric analysis (IGA). The key point of IGA is that it adopts the basis of CAD – such as B-splines and NURBS – to represent the geometry as well as the solution field for numerical analysis. The accurate transition from geometry to numerical simulation makes IGA an ideal candidate for topology optimization applications in which the response on the boundaries and interfaces is critical. One such example is stress constrained topology optimization problems, that are strongly affected by the accuracy of the computed stresses on the boundary of the evolving structure. Despite some recent advancements in the context of single-material topology optimization, optimizing multi-material, stress constrained structures with precise evolving boundaries is still a challenge. This is the aim of the current work, in which we adopt IGA on unstructured meshes to simulate the response of evolving topologies.

In the proposed approach, the topology is defined following level set methods where a B-spline surface is used to parameterize the level set function. In each optimization iteration, the level set topology is mapped into a spline-based representation. The mapping procedure is executed using untrimming techniques on the unstructured mesh. Subsequently, by applying mesh refinement, the mechanical model that replicates the geometrical model precisely is constructed. The refinement techniques are accompanied by a process that accounts for extraordinary points and T-junctions. This leads to an analysis suitable model that is solved by IGA. The optimization problem is solved by the method of moving asymptotes (MMA), utilizing analytical sensitivity analysis.

We explore various problem formulations involving stress constraints, volume of the materials and stiffness measures such as compliance. A key feature is that the stresses are evaluated not only in the interior of each material domain, but also on points that are located along the exact boundaries, where high continuity of the solution field enables accurate stress evaluation. This capability is especially important in regions of stress concentrations. In the talk, we will present results of several test cases, and aspects of accuracy and efficiency – in comparison to existing approaches – will be discussed.

Immersed Boundary-Conformal Method: An isogeometric discretization for topology optimization?

Benjamin Marussig (TU Graz)

The smoothness and structure of isogeometric discretizations enable robust and efficient implementations of higher-order finite element schemes. These benefits of the utilized spline functions come to light, especially for boundary-conforming meshes. At the same time, generating such meshes presents challenges, particularly for complex geometries whose topology may change during the simulation. Immersed boundary methods offer an alternative to boundary-conforming meshes that mitigates the complexities of meshing procedures and frequent grid regeneration. Yet, they introduce other computational challenges: (1) numerical evaluation of integrals over cut elements, (2) imposition of boundary conditions on immersed boundaries, and (3) maintaining the stability of discrete function spaces, in particular in the presence of very small cut elements. This contribution presents an immersed boundary-conformal method (IBCM) to leverage the advantages of conformal discretization and immersed methods. After discussing numerical examples of problems with non-moving boundaries, potential obstacles for the application to topology optimization are highlighted.

Optimizing isogeometric discretizations using deep neural networks

Felix Scholz (JKU Linz)

joint work with Dany Rios, Thomas Takacs

Isogeometric function spaces over parameterized computational domains are generated by the composition of spline basis functions with the inverse of the parameterization. In isogeometric analysis, These spaces are used to represent approximations to functions defined over the computational domain as well as approximations to solutions to partial differential equations. When the function that is to be approximated has a singularity, it is usually necessary to increase the number of degrees of freedom around the singularity, typically by adaptive refinement of the employed spline space. In this talk we present ongoing research on an alternative to adaptive refinement where we do not increase the total number of degrees of freedom. Instead, we optimize the parameterization of the computational domain in such a way that the use of the current degrees of freedom is as effective as possible. To this end, we employ a feed-forward neural network that was trained to predict the optimal parameterization of a three-dimensional point cloud of fixed size for fitting with a quadratic polynomial surface. We evaluate this neural network on a number of point clouds sampled from the computational domain and find a parameterization that best approximates the network's prediction. In our experimental results, we observe that our method results in an improved approximation error compared to classical refinement of the discrete space.

Isogeometric analysis for solving topology optimization problems with precise and explicit boundary representation

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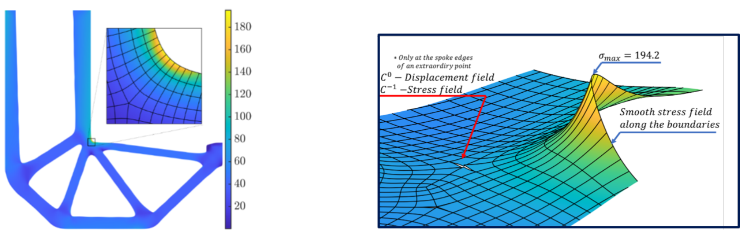
One of the current challenges in the field of topology optimization is to integrate accurate numerical analysis approaches that allow for precise resolution of the boundaries. The vast majority of studies in this field rely on finite element analysis (FEA). This requires representing the original structure geometry with an approximate representation that may lead to inaccurate estimations of physical measures, especially along the boundaries. So far, studies on this topic rarely adopt isogeometric analysis (IGA). The key point of IGA is that the analysis is performed over the original structure geometry where the structural boundaries are accurately represented. In principle, this could make IGA suitable for topology optimization problems with accurate boundary representations.

In the talk, a new approach for solving topology optimization problems will be presented. The main goal of the presented approach is to allow for accurate and explicit boundary representation within topology optimization. The topology is defined as a spline-based representation that is generated based on the level set method and constructed on an unstructured mesh. The procedure for generating the geometrical models is performed following untrimming techniques, leading to geometrical models whose boundaries are explicitly defined as cubic B-spline curves. The geometrical model is replicated precisely by mesh refinement to obtain a suitable model for subsequent IGA. Consistent sensitivity analysis is formulated to account for all mappings and refinements from the underlying level set function to the IGA-based solution of the mechanical response.

The proposed approach's applicability is demonstrated in compliance and stress minimization problems. Additionally, it is applied to benchmark stress-constrained topology optimization cases. A key advantage is that the stresses are computed not only in the interior of each patch but also in points that are located on the precise boundaries. Our results reveal the smoothness and accuracy of the stress evaluations on the untrimmed evolving boundaries, especially in regions of high-stress concentration. Extensions for applying the presented approach to solve other multiphase moving boundary problems, such as two-phase flow, will be discussed.



(a) (b)

Figure 1: Stress-constrained topology optimization results for an L-bracket. (a) Stress field over the optimized design. (b) Perspective view demonstrating the stress concentration region.

An Introduction to Isogeometric Analysis

Stefan Takacs (JKU Linz)

Starting from the origins and the original design goals of Isogeometric Analysis (IgA), we will discuss the main concepts of IgA as a tool for the numerical solution of problems involving partial differential equations. After recalling basic concepts, like the definitions of B-splines and Non-Uniform Rational B-Splines (NURBS), we will see a few possibilities how the geometry or computational domain can be represented and how the function spaces can be defined, we will see how the resulting Galerkin discretizations look like and which properties they have. Some of these approaches might be favorable for shape or topology optimization problems and we will discuss why. Certainly, also challenges of IgA are addressed.

Geometric Challenges in Isogeometric Analysis

Thomas Takacs (RICAM)

Splines are useful tools both for geometric modeling and for numerical analysis. While the approximation estimates of isogeometric discretization spaces on tensor-product B-spline patches and C0-matching multi-patch parametrizations are well understood, extending them to more complicated unstructured splines is not so easy. Depending on the way the unstructured spline spaces are defined, several problems can arise. In this talk we discuss some of the issues that can arise and study two phenomena in more detail: The loss of local polynomial reproduction due to higher order smoothness conditions of the spline spaces, and the loss of approximation power which derives from a specific type of refinement procedures that produce (in the limit) not sufficiently regular discretization spaces.

Isogeometric Analysis of Wrinkling

Hugo Verhelst (TU Delft)

Wrinkling is a phenomenon all around us. Besides being well-known in the context of cosmetics, wrinkling of membranes is a structural instability studied in multiple disciplines. From nanometer scale when studying the influence of wrinkles on the properties of graphene to kilometer scale when studying the influence of wrinkling on the structural stability of very large floating structures. From the aerospace for solar sails and space antennas, to the airspace for parachutes. From biomedical sciences studying wound healing to biological sciences studying brain morphology.

Since structural instabilities such as wrinkling are highly dependent on geometry as well as geometric imperfection, the role of the geometric description in computer simulations plays an important role. Therefore, isogeometric thin shell analysis provides an important tool in the analysis of the wrinkling phenomenon. Despite the momentum in isogeometric analysis in structural mechanics, wrinkling modeling remains a challenging topic, from the aspect of multi-scale analysis and the existence of multiple solution branches in the post-wrinkling regime.

This talk highlights the latest developments in the isogeometric analysis of wrinkling. It will provide a broad overview of the state-of-the-art of wrinkling modeling and applications, and it will present novel methods related to hyperelastic wrinkling modeling with isogeometric analysis, mesh adaptivity and complex domain modelling. In addition, an outlook on the application of these models on problems in shape and topology optimisation is provided.

Topology Optimization of a Magnetocaloric Refrigeration System with Isogeometric Analysis

Michael Wiesheu (TU Darmstadt)

The field of magnetocalorics is considered a promising alternative for environmentally friendly refrigeration. Cooling is achieved by cyclically magnetizing and demagnetizing magnetocaloric materials, which change their temperature according to the magnetic field variations. Permanent magnet assemblies are used to efficiently generate high magnetic field zones. To surpass the efficiency of conventional cooling technologies, it is necessary to find the optimal design of permanent magnets and achieve the highest possible magnetic fields.

In this work, topology optimization is used to compare different types of permanent magnet assemblies and to find the optimal arrangement of the magnets. The simulations are performed in 2D for the rotating magnet assembly in a framework with Isogeometric Analysis. The design domain for topology optimization is defined by a SIMP relation where the characteristics of soft iron or permanent magnets are applied. Different design variants are compared and the most suitable topology is selected for the further design process.