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‘DIRTY GEOMETRY’ AND SPLINE-BASED NUMERICAL ANALYSIS

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ABSTRACT

Geometry and topology of every domain of computation for a finite element analysis must fulfill certain suitability criteria. Most geometric models are created by CAD systems, where boundary representation schemes are predominately used. These B-rep models are usually considered valid or ‘analysis suitable’, if their faces form an orientable 2-manifold without a boundary [1]. From this, various requirements can be derived, such as (i) one edge is shared by exactly two faces, (ii) faces at one vertex belong to one vertex only, (iii) faces may intersect only at common edges and vertices, which in turn implies, that neither gaps nor double vertices, edges or faces may occur. Additionally, missing edges or faces are not allowed, the orientation of faces must follow Moebius’ rule, surfaces must not self-intersect, etc.

Numerous techniques have been developed to enable drafting analysis suitable models (T-Splines, T-NURCCs, analysis-aware modeling). However, the strict requirements given above are non-trivial to obey in everyday CAD, in particular, because topological and geometrical flaws often go unnoticed until mesh generation is applied. These ‘dirty geometries’ are difficult to transfer into analysis suitable models, and typically require geometry and mesh healing or even reconstruction techniques. Neither classical FEM nor IGA is constructed to avoid these labor-intensive healing steps. In the light of these observations, we present a methodology to directly use mathematically invalid, ‘dirty’ models containing topological and geometrical flaws for computational analysis. We construct a *valid* domain of computation, which differs from the given model only by ‘small’ geometric and topological modifications. To this end, the Finite Cell Method (FCM) is applied, which strictly decouples geometry and analysis. The FCM is an immersed boundary technique employing higher order polynomials [2] and/or spline-based shape functions. In the latter case, it can be interpreted as an extension of the Isogeometric Analysis to trimmed 3D solids [3]. At its core, the FCM requires only a Point Membership Classification (PMC), which can be constructed such that it is robust to flaws up to a user-defined accuracy. We will present a suitable PMC test, discuss its properties and demonstrate that a direct numerical analysis of dirty geometries is feasible, reducing the engineering effort for the transition from CAD to analysis drastically.

REFERENCES

[1] N. M. Patrikalakis, T. Sakkalis, und G. Shen, „Boundary Representation Models: Validity and Rectification“, in *The Mathematics of Surfaces IX*, Springer, London, 2000, S. 389–409.
[2] A. Düster, J. Parvizian, Z. Yang, und E. Rank, „The finite cell method for three-dimensional problems of solid mechanics“, *Comput. Methods Appl. Mech. Eng.*, Bd. 197, Nr. 45–48, S. 3768–3782, Aug. 2008.
[3] M. Ruess, D. Schillinger, A. I. Özcan, und E. Rank, „Weak coupling for isogeometric analysis of non-matching and trimmed multi-patch geometries“, *Comput. Methods Appl. Mech. Eng.*, Bd. 269, S. 46–71, Feb. 2014.

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CUT-CELL AND ISOGEOMETRIC METHODS: A SYNERGISTIC COMBINATION

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ABSTRACT

The concepts underlying cut-cell methods and isogeometric analysis can be synergistically combined to generate discretization workflows that bring about original and significant advantages in their own right. Over the last decade, this idea has been explored in a number of studies by several research groups (for an overview see for instance [1] and the references therein). The main purpose of this talk is to illustrate the large bandwidth of analysis scenarios, where this combination can significantly enhance capabilities compared to applying cut-cell methods or isogeometric analysis alone. The three different examples discussed in this talk include (a) the seamless integration of CAD models based on 3D boundary representations [2,3], (b) isogeometric shell analysis of trimmed CAD surfaces [4], and (c) cut-cell analysis of composites with asymptotic models of thin material interphases based on higher-order differential operators. For each example, we highlight methods-related challenges with possible solutions and briefly discuss avenues for future research.

REFERENCES

[1] D. Schillinger, M. Ruess, The Finite Cell Method: A review in the context of higher-order structural analysis of CAD and image-based geometric models. *Archives of Computational Methods in Engineering*, **22**, 391–455, 2015.

[2] A. Stavrev, L.H. Nguyen, R. Shen, V. Varduhn, M. Behr, S. Elgeti, D. Schillinger, Geometrically accurate, efficient, and flexible quadrature techniques for the tetrahedral finite cell method. *Computer Methods in Applied Mechanics and Engineering*, **310**, 646-673, 2016.

[3] Y. Zhao, D. Schillinger, B. Xu, Variational boundary conditions based on the Nitsche method for fitted and unfitted isogeometric discretizations of the mechanically coupled Cahn-Hilliard equations. *Journal of Computational Physics*, **340**, 177-199, 2017.

[4] Y. Guo, J. Heller, T.J.R. Hughes, M. Ruess, D. Schillinger, Variationally consistent isogeometric analysis of trimmed thin shells at finite deformations, based on the STEP exchange format. *Computer Methods in Applied Mechanics and Engineering*, **336**, 39-79, 2018.

DEVELOPMENT OF A NITSCHE-BASED, NON-INTRUSIVE, GLOBAL/LOCAL COUPLING ALGORITHM FOR IGA

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ABSTRACT

Due to an exact representation of the geometry and to the use of smoother and higher-order functions, the concept of isogeometric analysis [1], such as based on NURBS, enables to compute structures with an improved per-degree-of-freedom accuracy. However, in contrast to standard nodal finite elements (FEA), a multivariate NURBS basis comprises a rigid tensor product structure which precludes the simple modeling of local phenomena. In other words, we necessarily end up with a structured mesh in a NURBS. This unavoidably leads to the overlap of some global knot-span elements to allow for a truly global mesh-independent local region to be incorporated.

In the context of multiscale global/local simulations, a new class of methods that revolves around the concept of non-intrusiveness has attracted large attention these last years. The basis of these strategies is to set up an iterative procedure that locally alter the global model without modifying its numerical operators. The methodology appears thus particularly competitive in the case of a local region that is expected to evolve (*e.g.*, to carry out the shape optimization of local entities, to model crack propagation, etc). In the field of IGA, the challenge when developing such a non-intrusive strategy is to handle non-conforming coupling interfaces (*i.e.*, interfaces that intersect through the global structured NURBS mesh).

In contrast to the existing non-intrusive strategies that rely on a Lagrange multiplier coupling, it is proposed in this work to develop a new algorithm that makes use of the non-symmetric Nitsche approach [2]. Given the robustness and simplicity of the coupling (no auxiliary fields, no dual space approximation, no stabilization parameters), it results in an accurate and efficient tool to compute any evolution of a local model within a fixed global NURBS one [3]. The performance of the algorithm will be demonstrated through the presentation of a series of elastic benchmarks. In addition, the potential of the developed non-intrusive solver to be used to perform structural optimization will be discussed to motivate future research in this direction.

REFERENCES

[1] J.A. Cottrell, T.J.R. Hughes, and Y. Bazilevs, Isogeometric analysis: Toward Integration of CAD and FEA, *Wiley,* 2009.

[2] D. Schillinger, I. Harari, M.-C. Hsu, D. Kamensky, K.F.S. Stoter, Y. Yu, and Z. Ying. The non-symmetric Nitsche method for the parameter-free imposition of weak boundary and coupling conditions in immersed finite elements. *Comput. Meth. App. Mech. and Engrg.*, **309**, 625-652, 2016.

[3] R. Bouclier and J.-C. Passieux. A Nitsche-based non-intrusive coupling strategy for global/local isogeometric structural analysis. *Comput. Meth. App. Mech. and Engrg.*, **340**, 253-277, 2018

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NEW AUTOMATIC APPROACHES FOR IGA ON TRIMMED 2D AND 3D DOMAINS

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ABSTRACT

In this work we propose a new methodology for performing isogeometric analysis on volumetric geometries (V-reps), constructed using the IRIT modeler [1] through boolean operations and trimming. It allows to use isogeometric discretizations for 2D and 3D spline trimmed domains in a fully automatic way.

CAD geometries are tipically described as results of boolean operations on simple shapes (also BSpline and NURBS). When trying to assemble element by element the operators of a discrete variational problema on a trimmed domain, it is immediately clear that integrals for the Bézier elements affected by boolean operations are not easily computable: only the part of the element inside the computational domain must be integrated.

We present two different strategies for creating suitable quadrature formulas for trimmed elements: a first approach (only for 2D currently) re-parametrizes trimmed elements by splitting them into spline patches (tiles); a second methodology consists in meshing "à la finite elements" every trimmed element, using high-order finite elements (tiles). Thus, suitable quadrature formulas are created by gathering a set of quadratures, one for every tile of the re-parametrization.

The method presents optimal approximation properties for any degree when the same polynomial order is used for the tiles description and the discretization of the unknowns. Numerical results that support this theoretical result are presented, as well as examples involving complex 3D geometries that illustrate the potential of the method.

REFERENCES

[1] http://www.cs.technion.ac.il/~irit/index.html

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ISOGEOMETRIC TRIMMED SHELL ANALYSIS: FROM STRUCTURED TO UNSTRUCTURED MESHES

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ABSTRACT

Trimming does not change the parametrization of the underlying CAD surfaces which constitutes a roadblock to using trimmed geometric models in isogeometric analysis. In this work, we present two different approaches that enable isogeometric shell analysis of trimmed CAD surfaces. In the first approach, a generic and comprehensive design-through-analysis framework is discussed which enables automatic interaction with CAD data structures based on the STEP exchange format [1]. A STEP file contains all the essential information that can be transferred into quadrature rules for trimmed elements and along multi-patch coupling interfaces. In the second approach, alternative to the above framework, we also present a triangular Kirchhoff-Love shell element based on G^1-smooth Bernstein-Bézier triangulations of trimmed CAD surfaces [2,3]. We briefly talk about a surface technology to generate unstructured triangular meshes that are geometrically accurate and analysis suitable, eliminating the problems that occur when remeshing trimmed surfaces with tensor-product NURBS representations. To prevent a hinge-like rotation between Bernstein-Bézier triangles, Nitsche's method is used for the weak enforcement of interface constraints. We demonstrate that both approaches are suitable choices to seamlessly and accurately perform linear and non-linear stress analysis of industry-scale trimmed shell models, including a 76-patch Dodge RAM hood structure.

REFERENCES

[1] Y. Guo, J. Heller, T.J.R. Hughes, M. Ruess and D. Schillinger, Variationally consistent isogeometric analysis of trimmed thin shells at large deformations based on the STEP exchange format, *Computer Methods in Applied Mechanics and Engineering*, **336**, 39-79, 2018.

[2] S. Xia, X. Wang and X. Qian, Continuity and convergence in rational triangular Bézier spline based isogeometric analysis, *Computer Methods in Applied Mechanics and Engineering*, **297**, 292-324, 2015.

[3] L. Engvall and J.A. Evans, Isogeometric triangular Bernstein-Bézier discretizations: Automatic mesh generation and geometrically exact finite element analysis, *Computer Methods in Applied Mechanics and Engineering*, **304**, 378-407, 2016.

LEAST-SQUARES STABILIZED NITSCHE AND BASIS REMOVAL IN CUT ISOGEOMETRIC ANALYSIS

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ABSTRACT

We present a new stabilized symmetric Nitsche method, see [1], for enforcement of Dirichlet boundary conditions for elliptic problems of second order in cut isogeometric analysis (CutIGA). We consider C1 splines and stabilize the standard Nitsche method by adding certain elementwise least squares terms in the vicinity of the Dirichlet boundary and an additional term on the boundary which involves the tangential gradient. We show coercivity with respect to the energy norm for functions in H2(Ω) and optimal order a priori error estimates in the energy and L2(Ω) norms. To obtain a well posed linear system of equations we combine our formulation with basis function removal which essentially eliminates basis functions with sufficiently small intersection with Ω. For splines spaces basis function removal can be done in a rigorous way leading to optimal order convergence, see [2]. The upshot of the formulation is that only elementwise stabilization is added in contrast to standard procedures based on ghost penalty and related techniques, which lead to additional fill in. Furthermore, the analysis involves computable constants leading to an explicit lower bound on the Nitsche stabilization parameter. In our numerical experiments we find that the method works remarkably well in even extreme cut situations using a Nitsche parameter of moderate size.

REFERENCES

[1] D. Elfverson, M. G. Larson, and K. Larsson, A New Least Square Stabilized Nitsche Method for Cut Isogeometric Analysis, *arXiv*:1804.05654, 2018.

[2] D. Elfverson, M. G. Larson, and K. Larsson, CutIGA with Basis Function Removal, *Adv. Model. Simul. Eng. Sci., 5(6):1-19*, 2018.