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An interactive geometry modeling and parametric design platform for isogeometric analysis

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ABSTRACT

In this paper an interactive parametric design-through-analysis platform is proposed to help design engineers and analysts make more effective use of Isogeometric Analysis (IGA) to improve their product design and performance. We develop several Rhinoceros (Rhino) plug-ins to take input design parameters through a user-friendly interface, generate appropriate surface and/or volumetric models, perform mechanical analysis, and visualize the solution fields, all within the same Computer-Aided Design (CAD) program. As part of this effort we propose and implement graphical generative algorithms for IGA model creation and visualization based on Grasshopper, a visual programming interface to Rhino. The developed platform is demonstrated on two structural mechanics examples—an actual wind turbine blade and a model of an integrally bladed rotor (IBR). In the latter example we demonstrate how the Rhino functionality may be utilized to create conforming volumetric models for IGA.

1. Introduction

In recent years, the development of Isogeometric Analysis (IGA) [1,2] has paved a path towards a tighter integration of engineering design and computational analysis. The core idea of IGA is to use the same basis functions for the representation of geometry in Computer-Aided Design (CAD) and the approximation of solution fields in Finite Element Analysis (FEA). As a result, a single geometric model can be utilized directly as the analysis model. This approach bypasses the labor-intensive mesh generation process required for analysis, and has great potential to significantly improve the efficiency of design-through-analysis cycle.

Several computational geometry techniques have been used in IGA. Non-uniform rational B-splines (NURBS) [3–5] are the industry standard for geometry modeling and are most widely used in engineering design. NURBS are convenient for free-form surface modeling and can represent all conic sections exactly. There are many efficient and numerically stable algorithms [4], as well as commercial software packages (e.g., Rhinoceros—typically abbreviated Rhino [6]), that can generate and manipulate NURBS objects. Besides the geometric flexibility, NURBS also have excellent approximation properties [7,8] necessary for accurate analysis. Therefore, NURBS, a CAD standard representing many years of development, were a natural starting point for IGA [1]. T-splines [9,10] were introduced in the CAD community as a generalization and extension

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of NURBS allowing for local refinement and coarsening, and representation of geometry of arbitrary topological genus. T-splines have been applied successfully in the context of IGA [11–16] and have been further improved to meet the demands of analysis [17–20]. Recent attempts to construct trivariate solid T-splines can be found in [21–28].

IGA has been successfully employed in many areas of engineering and sciences, such as fluid mechanics and turbulence [29–38], solid and structural mechanics [39–55], fluid–structure interaction [13,56–63], phase-field modeling [64–68], complex fluids [69,70], Lagrangian shock hydrodynamics [71,72], contact mechanics [16,73–80], and optimization [81–84]. In most cases, IGA showed a clear advantage over standard low-order finite elements in terms of solution per-degree-of-freedom accuracy. This enhanced accuracy is in part attributable to the higher-order smoothness of the basis functions employed. Recent research directions in IGA include collocation [85–92], quadrature rules [93–96], trimmed geometries and patch coupling [97–102], analysis-suitable trivariate model [25–28,103–107], and standardized file formats for data exchange between geometry modeling and computational analysis software [108–112]. For more details of mathematical developments, basis function research, geometry modeling, model quality assessment, and early applications, the reader is referred to [2] and references therein.

With the success of IGA, one research direction has been the realization of IGA design-through-analysis workflow. The concept of IGA design-through-analysis framework was proposed in [14] based on hierarchical refinement of NURBS, T-splines, and Finite Cell Method [113–117]. The framework is suitable for solving three-dimensional solid-geometry problems by immersing the surface model into a background fictitious domain, a methodology recently termed *Immersogeometric Analysis* [63]. Refs. [118,119] present concrete instantiations of the design-through-analysis workflow implementation in actual CAD software. Ref. [118] laid out many of the core ideas for a design-through-analysis workflow for nonlinear shell structures, and, much like the present paper, made use of Rhino as the development platform. Ref. [119] presented an Analysis in Computer Aided Design (AiCAD) concept using NURBS-based B-Rep models and isogeometric B-Rep analysis (IBRA) method for nonlinear shell analysis. This more recent work included enhancements such as the ability to perform analysis in the presence of trimmed surfaces and the use of Nitsche's method for patch coupling. AiCAD has been implemented in two CAD software packages, Rhino and Siemens NX [120].

Despite the progress achieved in the last few years, several challenges remain in effectively using IGA to improve the engineering design process. Perhaps the biggest challenge is the rapid, (semi-)automatic construction of geometric models suitable for analysis. However, the difficulties of constructing designs and the corresponding geometric and analysis models are often overlooked in the engineering literature. It is often a time-consuming and challenging process to construct a baseline IGA model, and to ensure the model has the desired features such as good parameterization, sufficient mesh density in the regions of interest, and, most importantly, analysis suitability. In many cases intimate familiarity with CAD technology and advanced programming skills are necessary to successfully build such models. Design engineers, while good professional in their application areas, may not have such skills. Furthermore, in many cases, engineers are only interested in a handful of design parameters and how they affect the product performance. As a result, to help design engineers and analysts make more effective use of IGA, we propose in this work to develop an interactive IGA design-through-analysis platform based on the idea of parametric design and geometry modeling.

The proposed interactive geometry modeling and parametric design platform can streamline the engineering design process by hiding the complex CAD functions in the background through generative algorithms, and letting the user control the design through key design parameters. Since the design concept is integrated with analysis, the design parameters can include not only the geometry parameters, but also quantities such as material properties, loads, and boundary conditions. In this work, the concept of parametric design and geometry modeling is realized through a visual programming interface called Grasshopper [121], which is widely used by designers focusing on exploring new shapes using generative algorithms in Rhino. One advantage of using Grasshopper for parametric design and geometry modeling is that, during the CAD model generation, one can design the generative algorithm to ensure that the resulting IGA model is analysis-suitable.

The concept of *parametric modeling* is central to design in many fields of engineering and beyond (e.g., architecture [122]). Currently parametric modeling is used in conjunction with solid geometry modeling that employs geometric primitives and Boolean operations (e.g., SOLIDWORKS [123]). The use of parametric modeling with modern Spline technology like NURBS or T-splines is not common, and presents a novel research direction in IGA. The proposed work builds on the concept of parametric modeling and provides a fairly general and convenient approach for creating parametric designs, which make use of NURBS and T-spline geometry description, using the visual programming concept. The proposed approach is applicable to a large class of geometries, including surface and volumetric descriptions.

Another novel and unique aspect of this work is the development of the IGA visualization tool directly within Rhino CAD software. Good-quality visualization of the IGA simulation results is not a trivial matter. In many cases this is done by interpolating the IGA solution with low-order finite-element functions, and outputting the results using a standard finite-element data structure for visualization using existing software. However, in this work, we propose a procedure and develop a Rhino plug-in that can be used to visualize NURBS and T-spline analysis results directly in Rhino.

Finally, in the context of template-based modeling [35,57,103], we also demonstrate how Rhino functionality may be used to help construct volumetric (trivariate) NURBS models.

The paper is outlined as follows. In Section 2 we describe the salient features of the parametric IGA design-through-analysis platform. In Sections 3 and 4 we present two examples that further describe the inner workings of the proposed platform. In Section 3 we present an example of a wind turbine blade, which is treated as a composite shell structure. We demonstrate how the proposed tool can be used in a visual programming environment to: a. Create the blade geometry;