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Adaptive Refinement of Hierarchical T-splines

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Abstract

We present an adaptive local refinement technique for isogeometric analysis based on hierarchical T-splines. An element-wise point of view is adopted, which exploits Bézier extraction, and allows adaptive refinement of standard hierarchical T-splines and truncated hierarchical T-splines in a straightforward and unified manner. No explicit basis function operations are required to build the hierarchical basis function space, as only matrix manipulations are involved. This makes the efficiency superior to that of existing implementations. In particular, the implementation of truncated hierarchical T-splines requires no explicit truncation of the basis functions. In the analysis, a multi-level T-mesh is constructed by successive cell subdivisions of an initial, coarse T-mesh. An important feature is that Bézier extraction is employed to compute the refinement operator between two successive hierarchical levels, and that, at each level, Bézier extraction is applied to obtain the stiffness matrix without, initially, considering multi-level interaction. This interaction is recovered through a subdivision operator. Numerical examples are presented for validation purposes, and to assess the convergence properties.

Keywords: Hierarchical T-splines; Bézier extraction; isogeometric analysis; adaptive refinement

1. Introduction

A main advantage of isogeometric analysis is that NURBS functions commonly employed in the Computer Aided Geometric Design model, can directly be employed in the analysis model [1, 2], thus reducing the effort expended in (re)meshing, and improving, or even eliminating the error committed in the geometry description. However, the tensor product structure of NURBS prevents local mesh refinement. To obviate this drawback, various local refinement strategies have been proposed, including T-splines [3–5] and hierarchical and truncated hierarchical T-splines as further developments [6–8], LR-splines [9–12], hierarchical and truncated hierarchical B-splines [13–18], and PHT-splines [19–21]. It is further noted that adaptive splines also behold promise as an effective tool for local refinement in isogeometric analysis [6, 7, 13, 17, 22].

T-splines were introduced by Sederberg [3, 4]. They remove the rigidity of the tensor product structure of NURBS by allowing extra vertices to be inserted. Their first use in (isogeometric) analysis is in Reference [23], and the possibility to use them in existing finite element datastructures through Bézier extraction has been described in [24]. Mathematical properties of T-splines, for instance linear independence and partition-of-unity property of basis functions, are given in [25–27]. The local refinement of T-splines has been investigated in [5–7, 28, 29]. Of particular relevance for the work reported here is Reference [6, 7], in which the concepts of hierarchical and truncated hierarchical T-splines were proposed. They enable to combine the ability to locally refine hierarchical B-splines with the geometrical representation capability of T-splines.

In this contribution, we will develop the adaptive hierarchical refinement of T-splines. An element-wise point of view, enabled through Bézier extraction, will be employed for implementation purposes. A multi-level, hierarchical T-spline mesh is generated by successive cell subdivisions of an initial, coarse T-spline mesh. At each hierarchy level the element stiffness matrices are obtained by applying Bézier extraction without, initially, considering multi-level interaction. This interaction is enforced through the introduction of a subdivision operator. Two cases are considered:

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