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Automatic merging of hexahedral meshes

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ABSTRACT

A generic algorithm is proposed to merge structured and unstructured hexahedral meshes automatically into one single valid finite element mesh of hexahedral, tetrahedral and pyramid elements. In view of the success of merging arbitrary tetrahedral meshes in addressing the industrial need for rapid modification, update and manipulation of meshed objects, the merging algorithm is extended to hexahedral meshes by first dividing each hexahedral element into five or six tetrahedral elements. Non-intersected hexahedral elements can be easily recovered from the merged tetrahedral mesh as the constituent tetrahedra as a subdivision of the original hexahedral elements are intact and present in the mesh. Like the merging of tetrahedral meshes, the procedure is robust and efficient as all operations such as loops of intersection, incorporation of intersection segments, partition of boundary surfaces and identification of regions of intersection are deterministic and topological. The mesh merging algorithm provides a means to combine, modify and insert new features to existing hexahedral and tetrahedral meshes. It is also a powerful tool to create new meshes from existing hexahedral and tetrahedral meshes through the Boolean operations. High-quality regular hexahedral elements of the original mesh generated by mapping or extrusion will be preserved, which is important for finite element analysis as hexahedral elements are sensitive to shape distortions. Examples with details for each step of the mesh merging process are presented to elucidate the main ideas of the algorithm.

1. Introduction

Nowadays, advanced industrial production and manufacturing will systematically go through the cycle of conception and specification, CAD geometrical modeling, data acquisition for simulation and meshing, finite element analysis and optimization. For a proper maintenance of the products and possible upgrades for subsequent additional requirements, another round of simulation and refinement may be necessary to meet the new challenges. However, for the sake of rapid turnaround, it is not a good idea to go right back to the early inception stage, as after cycles of refinements and updates, the finite element mesh might have a substantial departure from the CAD model, which is already outdated or simply not available at all. Furthermore, the new demands very often would just require a couple of minute adjustments of the original design and a few minor modifications of the existing finite element meshes will produce a new model for engineering simulation addressing to all the required changes.

Many physical phenomena and objects are three-dimensional in nature, and a rigorous analysis and meaningful simulation could only be done in terms of a solid mesh of tetrahedral and/or hexahedral elements. In view of this situation, there are significant advances in the generation of tetrahedral and hexahedral meshes [1,2]. While advanced meshing algorithm are available for the generation of isotropic and anisotropic tetrahedral meshes over complex three-dimensional industrial and biomechanical objects [3,4], a versatile mesh generator capable of generating high-quality unstructured hexahedral elements for finite element analysis of complex industrial objects is yet to be developed. Nevertheless, hexahedral elements are superior to tetrahedral elements in the following aspects. (i) High-quality structured regular hexahedral elements can be generated rapidly by means of mapping, extrusion and sweeping techniques, (ii) hexahedral elements could be generated following the domain boundary in layers and in alignment with important geometrical features for easy visualization and inspection, whereas the validity of tetrahedral meshes can only be verified by computer and (iii) low-order high-performance hexahedral elements are available [5,6], which are considered to be more computationally efficient than the tetrahedral counterparts.

Hexahedral meshes of various characteristics can be generated by different approaches as proposed by researchers working in diverse scientific and engineering fields, and a comprehensive account of the current status and difficulties of hexahedral meshing is given by Staten et al. [7]. Mapping, extrusion (drag method) and sweeping [8,9] are classical techniques in generating well-shaped structural hexahedral meshes rapidly over simple

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regular domains, whereas Rypl [10] extended the mapping process to construct hexahedral meshes over volumes bounded by two arbitrary end surfaces. Decomposition methods have been developed to subdivide complicated objects into simpler blocks, possibly convex in geometry, so that they could be conveniently meshed into hexahedral elements [11,12]. Object decomposition can also be based on medial axis and medial surface construction [13], which could in turn be defined with the aid of a Delaunay triangulation [14]. Unconstrained plastering hexahedral mesh generation by means of advancing-front approach on 3D decomposition primitives was proposed by Staten et al. [7]. Using graph theory to represent possible polyhedron decompositions into tetrahedra, Meshkat and Talmor [15] proposed a method to generate a mixed mesh of hexahedra, pentahedra and tetrahedra from an underlying tetrahedral mesh. Based on a grid to extract the basic geometrical features of the old mesh, Fernandes and Martins [16] presented an all-hexahedral remeshing procedure for the finite element analysis in metal forming. Hex-dominated meshes were generated over irregular geometries by means of packing rectangular solid cells, Yamakawa and Shimada [17]. Hexahedral meshes of variable element size to fit general curved boundary surfaces were generated by means of the Octree technique with a set of refinement templates, Ito et al. [18]. Staten et al. [19] put forward an algorithm to match and modify non-conforming quadrilateral interfaces so as to link up individual hexahedral meshes. Hexahedral meshes were generated from MR imaging data onto a multi-block grid to fit required curved surfaces, Ji et al. [20]. With the introduction of transition elements, quadrilateral and hexahedral meshes of variable element size were generated by recursive element subdivisions for adaptive refinement analysis, Lo et al. [21]. Peter et al. [22] carried out a forward and adjoint simulation of seismic wave propagation on unstructured hexahedral meshes created by the toolkit CUBIT [23]. Vartziotis and Wipper [24] proposed an efficient hexahedral mesh optimization algorithm based on geometric element transformation. This approach is particularly effective and attractive,

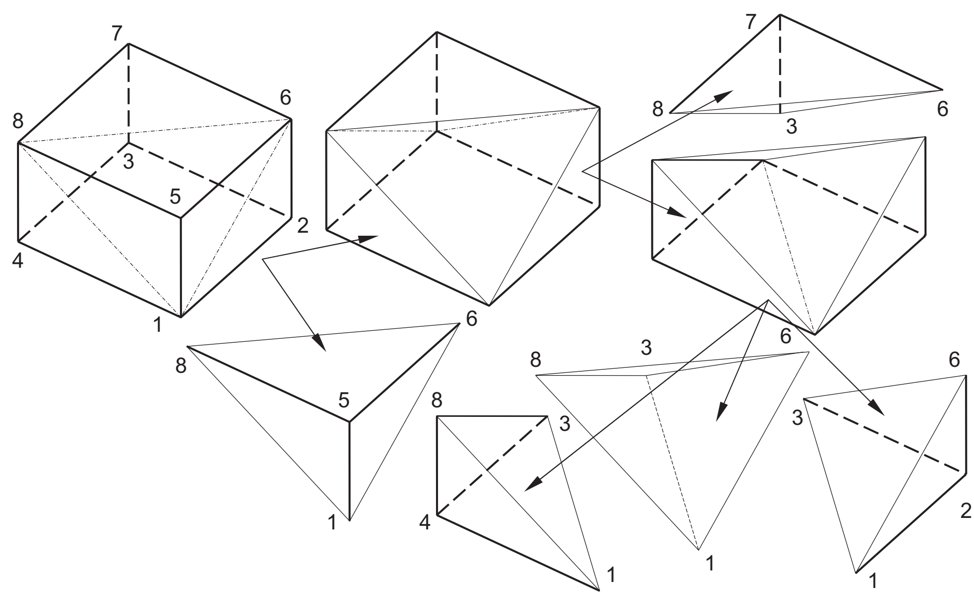

Fig. 1. Dividing a hexahedron into five tetrahedral.

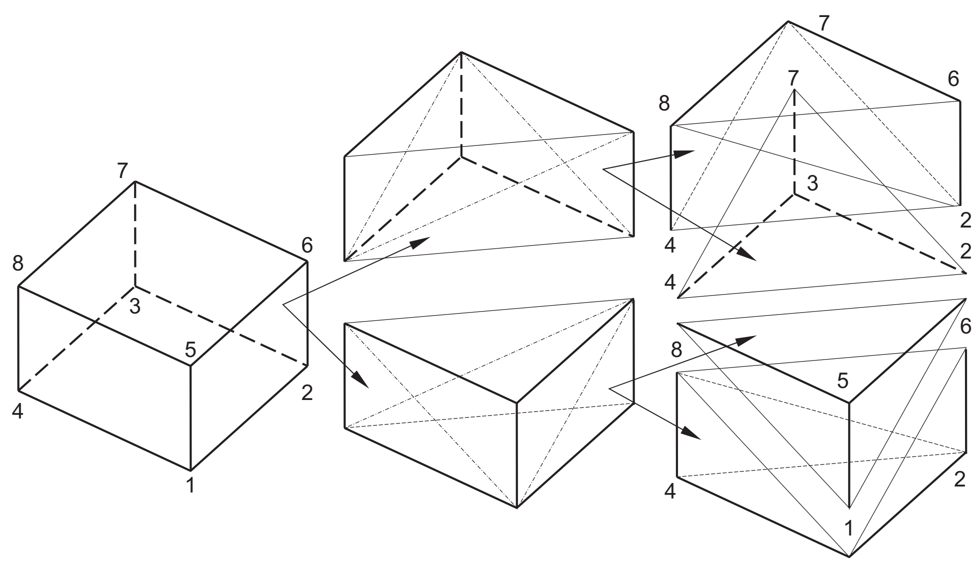

Fig. 2. Dividing a hexahedron into six tetrahedral.