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A Parallel Local Reconnection Approach for Tetrahedral Mesh Improvement

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Abstract

A multi-threaded parallel local reconnection algorithm is proposed for tetrahedral meshes. It defines a feature point within the region involved in each operation, and sorts the features points along a Hilbert curve. The decomposition of this Hilbert curve results in a load-balanced distribution of local operations. Meanwhile, the regions of concurrently executed local operations are separated far away, such that the possibility of interference is reduced to a very low level. Finally, a parallel mesh improver is developed by combining the proposed algorithm with a parallel mesh smoothing algorithm, and its effectiveness and efficiency is verified in various numerical experiments.

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Keywords: Mesh generation; Quality improvement; Unstructured mesh; Parallel algorithm; Multi-threaded

1. Introduction

The Delaunay triangulation (DT) [1-7] and the advancing front technique (AFT) [8, 9] are two of the most successful tetrahedral mesh generation approaches, although both approaches may generate low-quality elements. Firstly, they usually rely on surface inputs, and as a result the quality of a volume mesh is limited by the quality of its surface mesh. Secondly, both approaches are still far away from being perfect. The AFT mainly considers creating an element in each step of forwarding a front. After a number of front-forwarding steps, the fronts that

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define the unmeshed region may contain undesired geometry features. Low-quality elements have to be introduced to ensure the termination of the mesh generation process. With respect to the DT based approach, quality guaranteed algorithms have been proposed [8, 9]. However, their 3D versions are still problematic due to the issues of sliver elements and boundary integrity. Therefore, an improvement procedure must be followed after calling an AFT or a DT mesher to ensure the mesh quality meets the requirement of downstream simulations.

Although various improvement approaches have been proposed for tetrahedral meshes, the prevailing ones involve at least two types of local operations. One is smoothing, which repositions mesh points to improve adjacent elements [10-12]. The others are local reconnections [12-20], which replace a local mesh with another mesh that fills up the similar region but has different point connections. A general purpose improver usually needs to combine both types of operations and execute them iteratively [12, 13]. This process is demonstrated to be very time-consuming, in particular when the simulation needs a quality mesh containing hundreds of millions of elements. In our experience, a sequential Delaunay mesher can now generate one hundred million elements in about ten minutes [22]. Owing to the rapid advance of parallel algorithms, the time cost for a parallel mesher can be further reduced to a very low level [24, 25]. However, the following improvement procedure may take several hours to improve this mesh. If a higher standard is set for mesh quality, the time cost for mesh improvement can even grow to be larger than the sequential meshing time by several orders [13]. In this sense, the real performance bottleneck of generating tetrahedral meshes for complicated aerodynamics models lies in the phase of quality improvement rather than mesh generation itself.

Parallelization is a feasible way to speed up the mesh improvement procedure and enable it to handle large-scale meshes. Although parallel meshing algorithms have been extensively investigated in the literature [24-28], much fewer algorithms have been reported on parallel mesh improvement. In general, existing approaches for parallel mesh improvement could be classified into two types: *distributed parallel* approaches [25-27] and *multi-threaded parallel* approaches [11, 29].

Presently, distributed parallel approaches are preferred in some studies for their ability to employ sequential algorithms as a black box [25-27]. In these studies, the meshes to be improved (in most cases, these meshes are the outputs of a parallel mesher.) are usually subdivided into the same number of submeshes as the number of parallel processes involved in the mesh improvement task. Then, the input meshes could be improved concurrently by employing the sequential mesh improvement algorithm on each submesh with the inter-domain boundary fixed. However, the main issue is that elements may not be in shape near the inter-domain boundary. A possible solution to this issue is to introduce inter-process local operations to improve the elements in the neighborhood of the inter-domain boundary, based on the same idea as that introduced in a parallel Delaunay mesher [26]. These inter-process operations could be time-consuming because they involve a huge amount of communication and synchronization costs, not to mention the complication of their implementation. As a compromise, Ito *et al.* suggested a two-stage strategy to deal with this issue [27]. Firstly, the submeshes are improved concurrently with the inter-domain boundary fixed. Secondly, a few layers of elements adjacent to the inter-domain boundary are collected into a single mesh, and then this single mesh is improved sequentially. Evidently, the second stage could become a performance bottleneck due to its sequential nature. Differently, Löhner suggested redistributing the submeshes after the first pass of mesh improvement and then performing a second pass of mesh improvement on the redistributed submeshes [28]. Basically, the second mesh improvement pass could remove most badly shaped elements that the first pass is not able to treat, although survivors might be there if they are near the inter-domain boundary after shifting. Besides, because many elements are sent from the processes with high rank values to neighbouring processes with small rank values in the step of redistributing elements near inter-domain interfaces, the processes with small rank values may have to treat many more elements in the second mesh improvement pass than the processes with high rank values.

The preference of this study is a multi-threaded parallel approach, which attempts to utilize the local properties of mesh improvement operations. The pioneering work of this type was conducted by Freitag *et al.* [11]. Their parallel smoothing algorithm considers the region covered by elements adjacent to one single mesh point as an individual submesh. In order to avoid the synchronization costs required by the operations of repositioning adjacent mesh points, the mesh points are classified into many independent sets. The points belonging to the same set must not be adjacent to each other, where mesh points of different independent sets are differently colored. Evidently, the smoothing of points in the same point set is parallelizable.