Fraunhofer Institut
Techno- und
Wirtschaftsmathematik

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Berichte des Fraunhofer ITWM, Nr. 110 (2007)

ISSN 1434-9973

Bericht 110 (2007)

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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe sollen sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen werden.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

Parallel Software Tool for Decomposing and Meshing of 3D Structures

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8 March, 2007

Abstract

An algorithm for automatic parallel generation of three-dimensional unstructured computational meshes based on geometrical domain decomposition is proposed in this paper. Software package build upon proposed algorithm is described. Several practical examples of mesh generation on multiprocessor computational systems are given. It is shown that developed parallel algorithm enables us to reduce mesh generation time significantly (dozens of times). Moreover, it easily produces meshes with number of elements of order $5 \cdot 10^7$*, construction of those on a single CPU is problematic. Questions of time consumption, efficiency of computations and quality of generated meshes are also considered.*

Keywords: *a-priori domain decomposition, unstructured grid, Delaunay mesh generation.*

1 Introduction

The use of fully automatic generated unstructured tetrahedral meshes for highly complex domains can be one of the most efficient ways to solve large Computational Fluid

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Dynamics (CFD) and Computational Mechanics (CM) problems on parallel computers. While many solvers have been ported to parallel machines, grid generators have left behind. Grids in excess of ten million elements have become common for production runs in CFD and CM [1–5]. In CFD, a mesh of at least ten million tetrahedra can be required for high Reynolds number viscous turbulent flow simulation over a complete aircraft [6]. The expectation is that in near future grids in excess of $10^8 - 10^9$ elements will be required [7]. As mesh sizes become as large as this, the process of mesh generation on a serial computer becomes problematic in terms of time and memory requirements. Especially this is true for applications where remeshing is integral part of simulations, e.g. problems with moving boundaries [8–14] or changing topologies [15, 16], where the time required for mesh generation can easily consume more than 50% of the total time required to solve the problem [7]. In addition, the parallel overhead associated with partitioning a mesh generated on a single processor should be also avoided. Therefore, the need for developing parallel mesh generation technique is well justified.

A number of efforts have been reported on different algorithms and codes developed for parallel mesh generation in recent years. The most recent and extensive review of parallel mesh generation methods is given by N. Chrisochoides in [17]. The parallel mesh generated methods are classified in terms of two basic attributes: sequential technique to mesh individual subproblem and degree of coupling between the subtasks which determines the intensity of the communication and the amount/type of synchronization required between the subproblems.

In this paper we present a parallel 3D unstructured grid generator developed at Fraunhofer ITWM. The software package is based on a-priori geometrical partitioning of the computational domain into subdomains. The algorithm for meshing an individual subdomain is of Delaunay type and the subtasks are fully decoupled.

Developed algorithm is clearly advantageous in terms of computational time and memory usage compare to an a posteriori partitioning method used by mesh partitioning libraries such as (PAR)METIS [18]. It allows us to use well tested and fine-tuned sequential 2D and 3D triangulators which are capable of producing mesh with guaranteed quality. The algorithm achieves 100% code re-use and eliminates communication and synchronization. All operations performed preserve original surface mesh. The algorithm produces almost plane interfaces, i.e. interfaces with small perturbations between the subdomains and uses a splitting criterion, which minimizes the interface area and which is sensitive to both the object shape and the grid resolution. In spite of all these advantages the method consists of a sequence of steps, where almost all of them are simple, as opposite of sophisticated algorithms, which are used in other mesh generating methods.

Several real-life examples with complex geometries involving generation of large meshes are given ($10^7 - 10^8$ elements). It is shown that developed parallel grid generator significantly reduces mesh generation time and allows us to construct meshes which can not be generated on a single CPU because of memory limitations and large computational time.

Rest of the paper is organized as follows: Section 2 formulates the problem and gives description of the algorithm. In Section 3 several real-life 3D examples are considered. Then results are discussed in Section 4 and 5th section summarizes and concludes the paper.

2 Parallel generation algorithm

The goal of the work is to create a parallel grid generator for high-quality tetrahedral grids with good properties (e.g. Delaunay property) for solving PDEs. It should be fully automatic, adaptive (via coupling with the solver) and, of course, able to generate large meshes. The input data is a CAD surface description of an object. The algorithm consists of the following major steps:

1. **Decomposition of an object into open non-overlapping subdomains.**
    (a) computing of center of mass and inertia tensor computation to determine the cutting planes
    (b) extracting of all intersecting edges and construction a cross-section contour line.
2. **Construction of closed and compatible surface mesh for each subdomain.**
    Projection of contour nodes on a cutting plane, construction of 2D constrained Delaunay triangulation on the plane inside the contour and mapping back the contour nodes of the triangulation to original surface positions.
3. **Independent parallel volume meshing (without communication) within each subdomain based on and compatible with its surface mesh description.**

The flow chart of parallel grid generator is shown in Fig.1. Details of the algorithm are given in the following subsections.

2.1 Setting up the cutting planes

Here the center of gravity along with the moment of inertia criterion is used. Each object is cut perpendicular to its smallest principal inertia axis. It means that for each part with the set of nodes V, the inertia matrix is computed by

$$I = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix},$$

where matrix I is symmetric and

$$I_{ij} = \sum_{v \in V} \left[\left(x_l^v - x_l^g\right)^2 \delta_{ij} - \left(x_i^v - x_i^g\right)\left(x_j^v - x_j^g\right) \right].$$

Here (x^g, y^g, z^g) are coordinates of the center of gravity calculated by assigning unit mass to each node of the mesh. Thus, grid resolution is also taken into account. Then (one of) the eigenvector(s) with the smallest eigenvalue is selected.

This procedure defines planes perpendicular to the smallest principal inertia axis. The actual cutting plane is chosen to go through the center of gravity. This partitioning technique is sensitive to the object shape and grid resolution and can minimize the interface area.

Nevertheless, it turns out to be hard to find a reasonable criterion for predicting a good load balancing in advance. Even if the number of tetrahedra is approximately the same for each subdomain, the CPU time spent for the volume meshing of each part can be quite different [19].

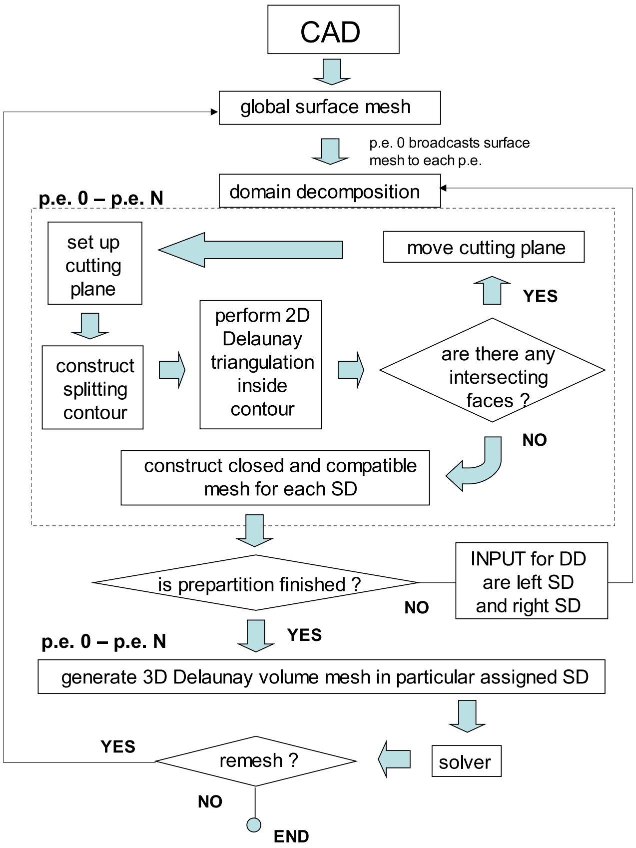

Figure 1: Flow chart of parallel grid generator.

2.2 Construction of the splitting contour

Once the cutting plane is defined, we can construct a cross-section contour where 2D constrained Delaunay triangulation will be performed.

Here we present improved technique of forming the splitting path of edges. The construction of the contour consists of the following steps:

1. Extract all intersected edges of the surface triangulation.
2. Remove all edges with "hanging" nodes.
3. Sort the edges into a closed loop.
4. Remove multiple paths if they are.

Procedure of forming the contour is shown in Fig.2. For more complex geometry configurations, especially involving corners and concavities, multiple paths can occur. Several examples of such incidents are illustrated in Fig.3. Special care is taken in order to remove all of these incidents.

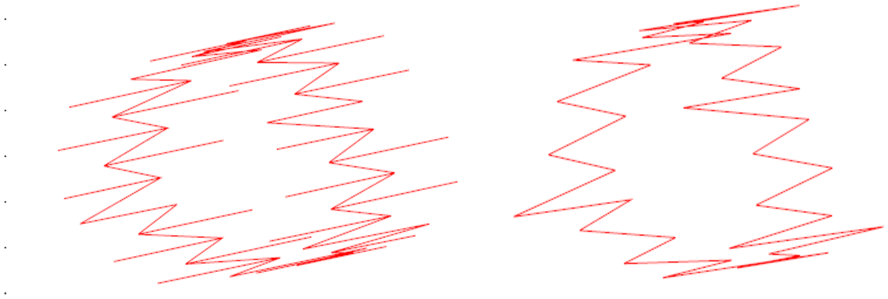

Figure 2: Construction of the splitting contour: extraction of all intersected edges and forming of closed curve of piecewise straight lines (segments).

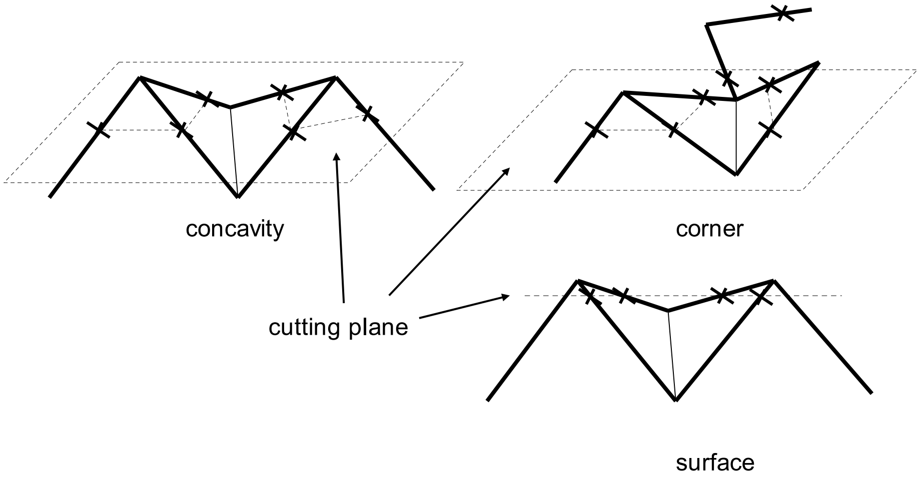

Figure 3: Incidents of multiple paths in case of concavity and corner.

2.3 Construction of interface

Two steps are required before the 2D triangulation of the interface can be done:

1. Mapping of the contour nodes on the cutting plane.
2. Rotation into $X - Y$ plane of the coordinates for 2D triangulation.

The program *Triangle* [20] from Shewchuk is used for the triangulation of the interface. However, also other Delaunay algorithms can be applied.

After triangulation of the interface with certain constraints on minimal angle and maximum triangle area, the coordinates are reversed back and the contour nodes are mapped back onto their original surface positions. It has been found that it can result in the intersection of triangular faces of the interface grid and the original domain surface grid. This happens when a straight line between two nodes, that form an edge of two-dimensional boundary, can not be drawn in three dimensions without intersection with another part of the mesh, that does not form part of the interface. This is

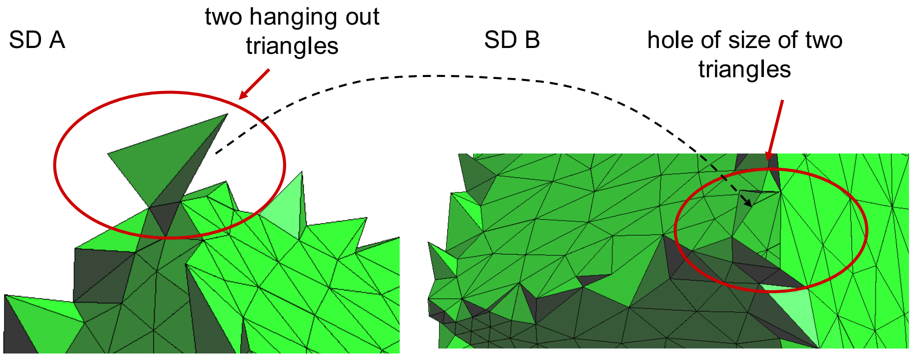

Figure 4: Hole in the mesh and moving of triangles according to special rule.

immediately detected and the cutting plane is moved on a certain step perpendicular to the minimal principal inertia axis till there are no any intersections. This procedure computationally is not expensive and requires only several reconstructions of two-dimensional interface mesh.

2.4 Construction of closed and compatible surface mesh for each subdomain

Produced surface meshes have to meet two major requirements: they should be waterproof, e.g. be void of holes, and consistent. These are necessary conditions for further generation of tetrahedral mesh inside.

So we have an original surface mesh and triangulated interface. Task is to split the original mesh and obtain two domains with the waterproof and consistent mesh. The general splitting rule for triangles is following: triangle belongs to a certain part if it has at least two vertices there.

There are some exceptions, where triangulation should be split in a different way. It concerns cases, where decomposition according to general rule results in holes in one subdomain and extra triangles in another (see Fig.4).

2.5 Overall domain decomposition & volume mesh generation

Automatic partitioning is done with use of inertial bisection algorithm, where new center of mass, eigenvectors and inertia axis are recomputed for every subdomain. So the overall domain decomposition of an object can be represented by the binary tree (see Fig.5). When the decomposition reaches prescribed number of subdomains (CPUs) it stops.

Now when partitioning is finished and a closed and compatible surface mesh is created for each subdomain at the last decomposition level, the volume meshes are constructed in parallel. *TetGen* - a quality tetrahedral mesh generator and three-dimensional Delaunay triangulator from Hang Si [21] has been used for volume Delaunay tetrahedralization with certain quality bounds (radius-edge ratio), a maximum

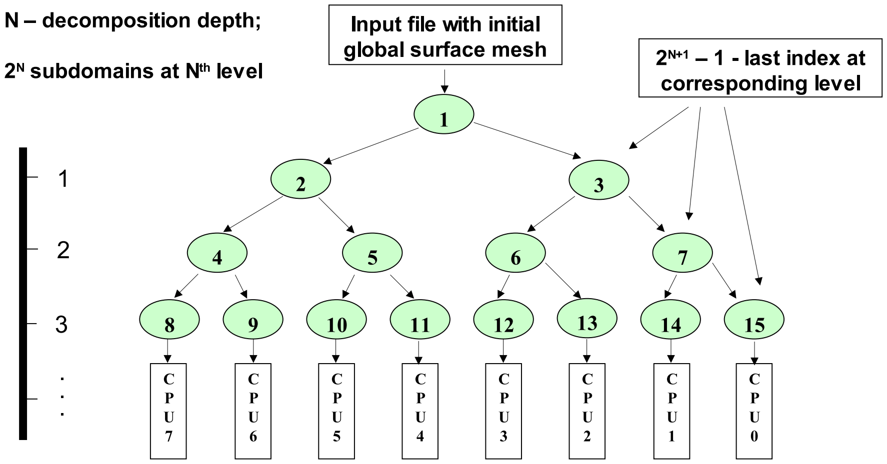

Figure 5: Architecture of overall domain decomposition.

volume bound, a maximum area bound on a facet, a maximum edge length on a segment.

3 Numerical test for real-life problem

3.1 Knee prosthesis components

As first two examples of volume mesh construction in complex domains by using described algorithm components of knee prosthesis produced by Lima Group [22] are taken. In Fig.6 and 7 an a priori decomposition of original surface meshes in these two cases are shown (16 and 8 correspondingly). It can be seen that the algorithm able to handle relatively complex geometries.

3.2 Bearing cap

Next example is a bearing cap to fix a crank shaft at a motor block [23]. This example will be further used for more detailed analysis of algorithm efficiency and quality of produced meshes.

In Fig.8 an a-priori decomposition of computational domain on 32 subdomains is shown.

The simulation was run on the Fraunhofer ITWM cluster with high - bandwidth /low-latency myrinet network: 64 nodes, each node has Dual Xeon CPU 2.4 GHz, 4GB RAM. Three meshes of different sizes were constructed. In Table 1 generation time on a different number of CPUs is given. In case of 400 thousands and 4 millions elements the computational time was reduced dozens of times owing to developed parallel grid generator. If generation of these two meshes is still possible on a single CPU due to reasonable size, then sequential generation of the third mesh with more than 40 millions elements fails. Developed parallel grid generator constructs this mesh on 32 CPUs in approximately 1.5 minutes. The speed-up of volume mesh generation time in

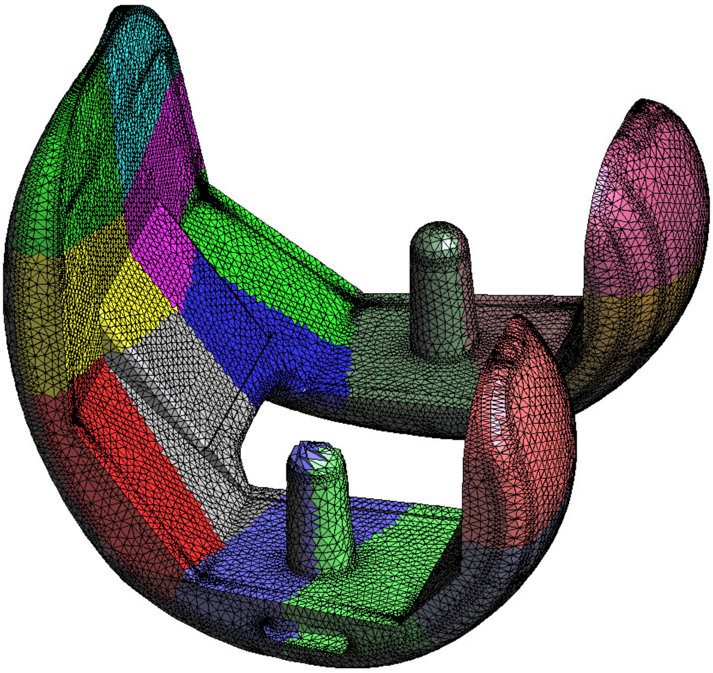

Figure 6: An a-priori domain decomposition of knee prosthesis femoral component on 16 subdomains.

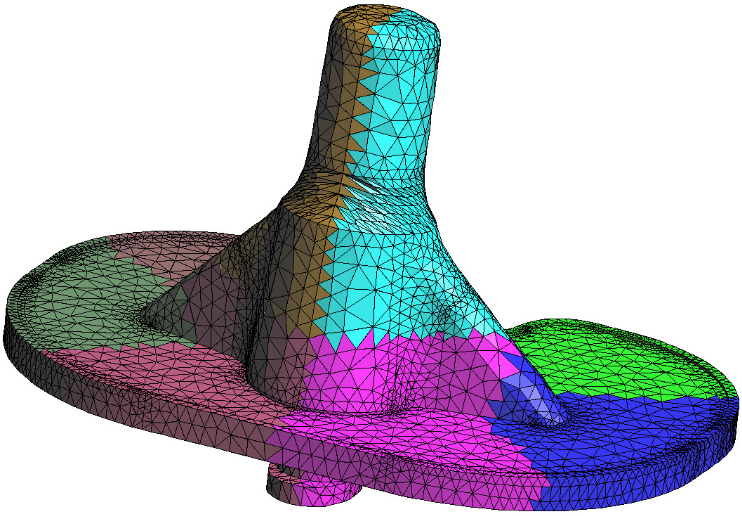

Figure 7: An a-priori domain decomposition of knee prosthesis tibial component on 8 subdomains.

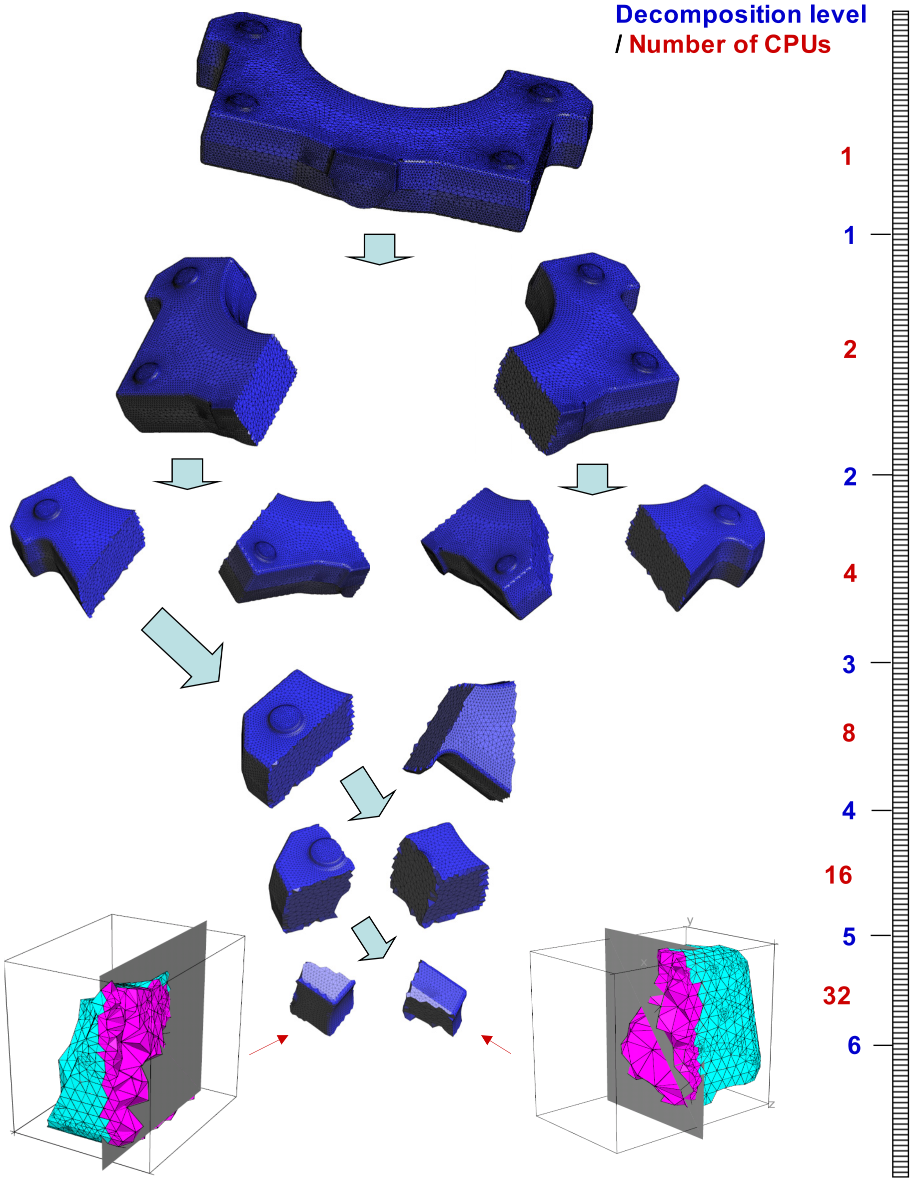

Figure 8: An a-priori domain decomposition of bearing cap component on 32 subdomains.

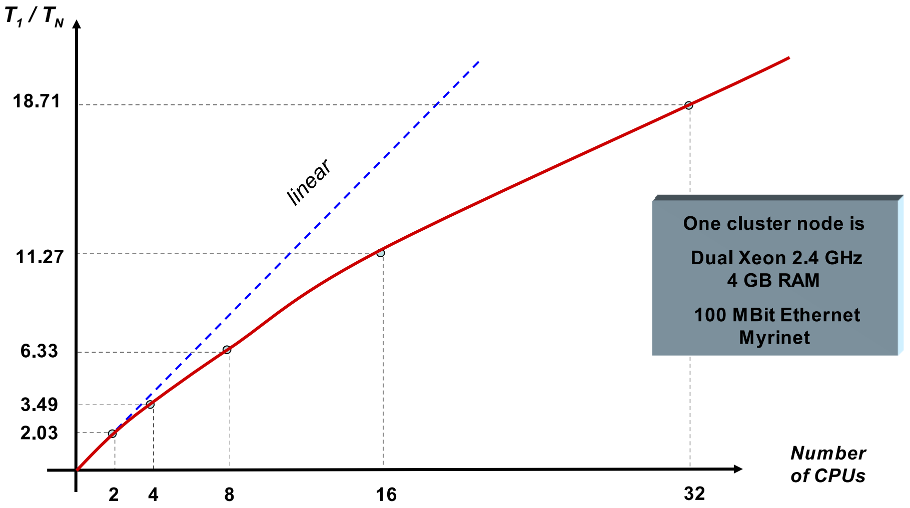

Figure 9: Speed-up of volume mesh generation time for the bearing cap geometry.

case of 4 million elements is given in Fig.9. As it is seen efficiency of the computations on 32 CPUs is about 60%.

Table 1: Computational time for construction of volume meshes of different sizes

Elements/CPUs	1	2	4	8	16	32
$4 \cdot 10^5$	20.91	10.26	5.78	3.30	2.54	1.25
$4 \cdot 10^6$	169.56	83.07	48.43	26.75	15.02	9.06
$4 \cdot 10^7$	failed	961.45	558.197	356.39	181.08	91.13

4 Results and discussion

Developed parallel grid generator helps to remove a computational bottleneck related with sequential construction of volume mesh. It can be used with parallel solvers providing prepared subdomain for each CPU as well as with other sequential solvers to reduce mesh generation time. In latter case subdomains should be joined back together into one global volume mesh (see Fig.10).

The quality of generated mesh should be acceptable by a solver. It means that mesh constructed by parallel grid generator and mesh generated sequentially on one CPU should not have big difference in quality. In Fig.11 distribution of tetrahedral elements according to shape quality is given for meshes constructed sequentially and

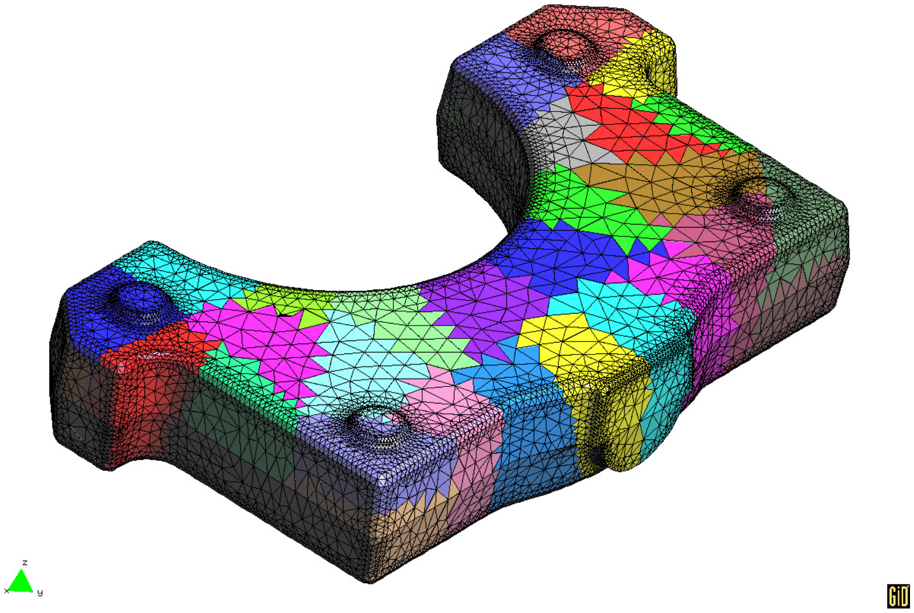

Figure 10: Volume mesh of a bearing cap constructed by parallel grid generator.

by using parallel grid generator. Here the shape quality Q is calculated by

$$Q = \frac{6\sqrt{2} \cdot Vol}{\sum_{i=1}^{6} \ell_i^3},$$

where Vol – tetrahedron volume, ℓ_i — lengths of its edges. For the regular tetrahedron $Q = 1$. It is seen that comparable quality is achieved. In both cases the greatest number of tetrahedra are with $Q \approx 0.76 \div 0.78$.

It happened to be hard to find a reasonable criteria for predicting a good load balance in advance. There is no direct relation between number of surface and volume elements. Number of surface elements is just a good indicator. Some unexpected results can appear. Even if number of volume elements in two subdomains is the same, CPU time spent on those two parts can be quite different. This could happen due to, for example, problems related with boundary irregularities.

Although significant progress has been made in devising solutions for certain classes of geometric domains, its solution for general domains is still an open issue. The disadvantage of this approach is the fact that the associated "optimal" partitioning problem is NP-complete for general regions [24]. However, as it has been seen, the described procedure allows us to generate very large meshes in relatively short time and in computationally efficient manner.

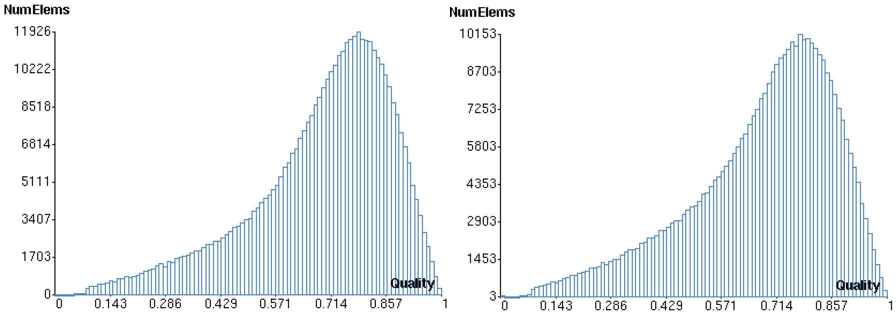

Figure 11: Distribution of elements according to their shape quality. Left — mesh generated sequentially. Right — mesh generated by parallel grid generator.

5 Summary and conclusion

In this paper we have presented a parallel algorithm and software for handling the mesh generation and decomposition preprocessing phases required by domain decomposition based parallel FEM computations. However, it can be used with sequential solvers to speed up mesh generation stage.

Developed algorithm is clearly advantageous in terms of computational time and memory usage compare to an a posteriori partitioning method used by mesh partitioning libraries such as (PAR)METIS. It allows us to use well tested and fine-tuned sequential 2D and 3D triangulators which are capable of producing mesh with guaranteed quality. The algorithm achieves 100% code re-use and eliminates communication and synchronization. All operations performed preserve original surface mesh. The algorithm produces almost plane interfaces, i.e. interfaces with small perturbations between the subdomains and uses a splitting criterion, which minimizes the interface area and which is sensitive to both the object shape and the grid resolution. In spite of all these advantages the method consists of a sequence of steps, where almost all of them are simple, as opposite of sophisticated algorithms, which are used in other mesh generating methods.

The main disadvantage of this approach is the fact that the associated ”optimal” partitioning problem is NP-complete for general regions. So it can be used for a certain class of geometric domains only.

However, it is demonstrated that very large meshes (up to 50 million elements) with complex geometry can be created. It is shown that developed software based on described algorithm is capable of producing large meshes in relatively short time and in computationally efficient manner. It is important to mention that quality comparable with sequentially generated mesh is achieved.

Further work on testing, creating of better programming interface with CAD, handling of examples with more complex geometries and larger meshes and performing local adaptive mesh refinement from CAD level is in progress.

Acknowledgment

This work is supported by the Fraunhofer Institute for Industrial Mathematics (Competence Center for High Performance Computing and Visualization), DAAD, TU

Kaiserslautern and Institute of Theoretical and Applied Mechanics SD RAS. The authors are grateful to Franz-Josef Pfreundt and wish to thank S.K. Godunov for his interest to this work and many comments on subject. The work is partially supported by the Kaiserslautern Excellence Cluster Dependable Adaptive Systems and Mathematical Modeling.

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