CGAL-Mesh
An Open Platform for Mesh Generation

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Summary. CGAL-Mesh is a two-year INRIA technological development action started in March 2009. Building upon components from the Computational Geometry Algorithm Library (CGAL), our goal is implement generic and robust mesh generation algorithms for surfaces and 3D domains, and later for time-varying 3D domains. We primarily target applications which involve data acquired from the physical world: geology, medicine, 3D cartography and reverse engineering. We wish to establish a close collaboration with industrial and academic partners so as to maximize the impact of the platform for a number of applications and research experiments.

Context

Surface and 3D meshes play a central role in numerical engineering for the simulation and visualization of physical phenomena. They are also commonplace for the modeling and animation of complex scenes for feature animation movies and multimedia applications. Surface meshes for rendering are requested to approximate well the object boundaries, and 3D meshes for numerical simulation must fulfill additional constraints over the shape, orientation and size of the elements.

The generation of 3D meshes of moderate size from "clean" input is not a critical issue, and many satisfactory solutions to this problem are available. Clean herein means for instance carefully designed parametric surfaces which are the common representation to engineering applications. Nevertheless, a growing trend in the applications is to deal with complex shapes either known only through *measurements*, obtained as combination of heterogeneous data sets, or automatically generated by imperfect algorithms. This is the case for, e.g., 3D images in medical imaging, seismic data for geophysics and laser scanned 3D point sets for reverse engineering. These issues explain why mesh generation often dominates the wall clock time of complex simulations using finite element methods. A closer look reveals that most of the time is spent at reconstructing from such data a surface suitable to the mesh generation algorithm. A common example of such reconstruction pipeline for 3D images is depicted Figure 1(top).

Another trend is to make use of meshes not just for rendering and simulation, but as means to solve other problems. Example of such problems include image segmentation for medical applications [11] and spatio-temporal coherent segmentation of time-varying data sets such as a beating heart. As for images, meshes are now commonly used as central data structures for a variety of algorithms, which are not necessarily close to geometric problems. This poses new challenges in terms of higher dimension, complexity as well as genericity of the mesh generation algorithms.

Distinctive Features

There is a plethora of commercial solutions for the automatic generation of 3D tetrahedron meshes. Some of them are included in CAD or simulation software packages for computational fluid dynamics or mechanical analysis. Although the open source offer is much more limited, we can cite NETGEN from the University of Linz, GRUMMP from the University of British Columbia and TETGEN from the Weierstrass Institute of Berlin. They all share the common feature that the domain boundary must be provided as a clean polyhedral surface mesh or parametric surface, and hence are not very generic in that respect.

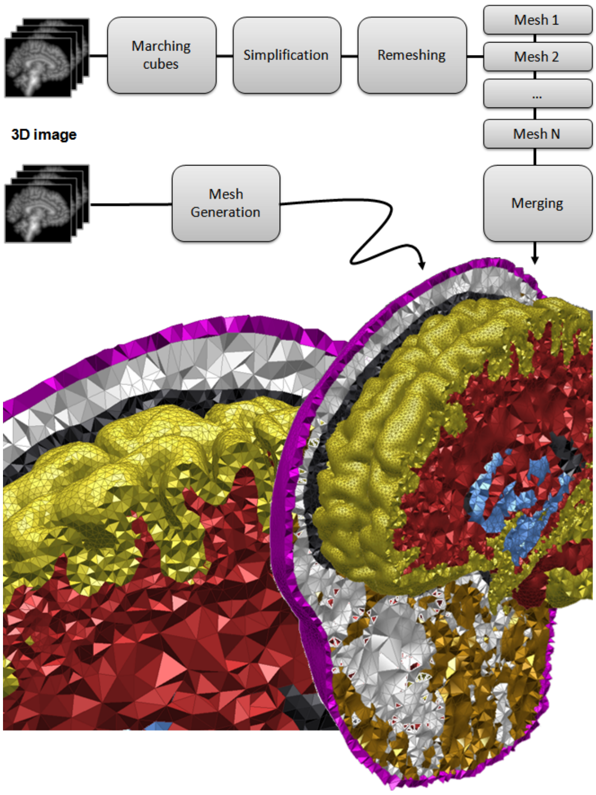

Figure 1: Mesh generation from 3D images. The common pipeline applies marching cubes to extract isosurfaces, simplification, remeshing, 3D mesh generation separately for each domain and finally merging of all 3D meshes. Our mesh generation technique generates a multi-domain 3D mesh at once from 3D images. The output mesh is by construction conforming at all domain interfaces, and the whole process does not require trial-and-error processes.

Furthermore, most of them require a quality surface mesh as input (with well-shaped triangles) as they preserve, instead of approximating it. The preparation of such quality mesh from defect-laden inputs requires applying a sequence of algorithms, which is notoriously labor-intensive and prone to robustness issues.

In higher dimensions the offer is considerable smaller. Algorithms for time-varying data sets (3D+T) are often imperfectly derived from 3D algorithms. To our knowledge, there is no generic mesh generation software for higher dimensions, while some needs exist for simulation of complex physical phenomena.

In the recent past, the GEOMETRICA project-team has developed solid foundations for mesh generation and has gained a visible position in the field. The paradigms proposed are amenable to a robust, unified and generic approach to mesh generation, and for a variety of application contexts [13]. We now review the main strengths which make our approach distinctive.

- **Genericity:** The algorithms implemented are separated from the representations of the input domain. This is obtained through so-called *oracles* which provides domain queries to the core meshing engines in an abstract and generic manner. We have already implemented oracles for gray-level 3D images, multi-domain 3D images, implicit surfaces, polyhedral surfaces and 3D point sets. Figure 1 and 3 illustrate two different oracles. New oracles specialized to other application domains can be implemented in a flexible and well structured manner.
- **Robustness:** As the algorithms are based upon components from the CGAL library they benefit from most of its virtues: Efficiency[1], robustness and interoperability with other components from the library. Robustness is achieved through careful studies of arithmetic and degeneracy issues. Note that as the number of robustness issues is partly related to the complexity of data (constantly increasing in industrial applications), robustness of the algorithms is a real advantage for the future.
- **Guarantees:** The main ideas behind our algorithms rely on simple and robust paradigms such as Delaunay refinement and filtering, which are amenable to theoretical analysis and translate into practical guarantees over the output mesh quality and complexity. Guarantees and robustness altogether translate into reliable software for the end user.
- **Openness:** The platform benefits from the diffusion of the CGAL open source project to a community of users and developers[2], which ensures a continuous feedback and improvement, as well as new extensions for the library.

[1] Computing the 3D Delaunay triangulation of 10M tetrahedra takes 45s on a recent desktop computer (Intel P4 3GHz).

[2] 40 active developers, 50 industrial customers, 1000 users of the mailing list, and overall several thousand users.

Figure 2: Mesh generated from a segmented grey level 3D image of a bone (data courtesy INSERM).

Functionalities

The following components are already available as modules of the CGAL library:

- **Isotropic triangle mesh generation** for 2D polygonal domains with or without internal constraints. The user can control the size and shape of the triangles.
- **Isotropic tetrahedron mesh generation** for 3D domains defined by implicit functions, polyhedral surfaces and gray-level 3D images. The user can control the size and shape of the tetrahedra, as well as the boundary approximation error. Complex multi-domains such as segmented 3D images are also handled within the same framework while conforming the meshes at the domain interfaces [6, 7]. A special handling of sharp features ensures, when required, a fair representation of boundary surface creases in the mesh [6, 15]
- **Tetrahedron mesh optimization** so as to trade mesh quality for efficiency [1, 16]. The procedures are optionally applied after mesh generation.
- **Smooth Surface reconstruction** from (possibly noisy) unorganized 3D point sets. We also provide a complementary component for processing raw point sets (denoising, normal estimation and orientation, etc). Robust surface reconstruction is in our current research planning [14, 9], and we also carry on research on manifold reconstruction [2].

The following components will be made available in upcoming releases of the CGAL library:

- **Anisotropic tetrahedron mesh generation** where the mesh tetrahedra conform to a user-specified metric field [5].
- **4D simplicial and higher dimension mesh generation** for, e.g., time-varying 3D domains such as live organs in medical applications [].

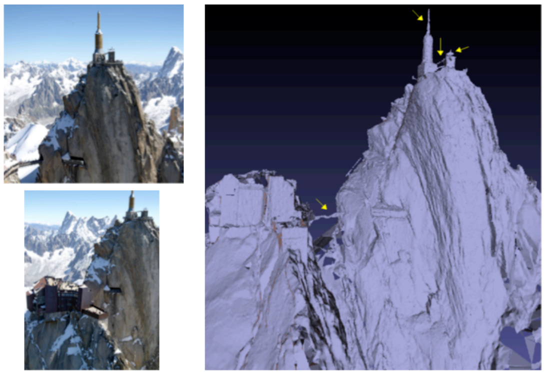

Figure 3: Simultaneous surface reconstruction and surface mesh generation from stereo vision data. Left: a few images of the“Aiguille du Midi”. Right: a quality triangle surface mesh generated by querying an oracle elaborated on top of a reconstruction procedure from stereo vision data.

Collaborations and Transfer

The current open platform for mesh-generation is aimed at speeding-up and strengthening research and industrial development in various application domains. In addition, we wish to disseminate this platform toward researchers in mesh generation, as the genericity of our approach allows for effective experiments.

The output of CGAL-Mesh project is distributed as part of the CGAL library. The license model adopts the dual one of CGAL , which is both open source and commercial (see `http://www.cgal.org/license.html`).

Our main transfer vector is the spin-off GeometryFactory (`http://www.geometryfactory.com`) which integrates and commercializes all CGAL components for those (industrial and academic developers) who do not conform to the open source model. We are also open to other collaborations and we wish in particular to establish collaboration with industrial and academic partners. Our goal is to benchmark on real application test cases, receive feedback and most importantly to ensure along the way of our developments that we are in line with the most enduring constraints posed by industrial applications as well as by research experiments.

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For a complete list see `http://www-sop.inria.fr/geometrica/publications`.