ADT CGALmesh

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presentation by Monique Teillaud

Journées nationales des ARC, ADT et Actions Exploratoires
Novembre-Décembre 2010

ADT CGALmesh

March 2009 - March 2011

People

From EPI Geometrica:

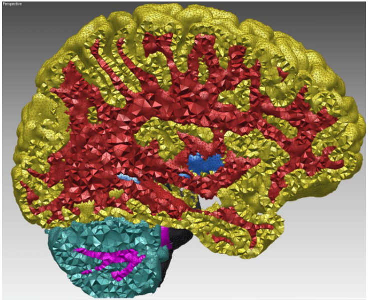
Researchers: Pierre Alliez, Jean-Daniel Boissonnat, Mariette Yvinec
Post-doc: Dobrina Boltcheva
Phds : Jane Tournois, Nader Salman

Dream ingeneer(2 years funded by the ADT): Stéphane Tayeb
From Geometry Factory: Laurent Rineau
External partners: IRCAD, BRGM, CSTB, Distène.

Goal

Develop an open platform for mesh generation
based on the CGAL library http://www.cgal.org,
aiming at generation of simplicial meshes: 2D, 3D and surface meshes.
Preferred targeted applications in medical imaging, geological reconstruction

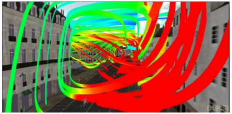
Motivations



Good simplicial meshes

- Well shaped elements
- Appropriate sizing of elements
- Accurate approximation of boundaries and internal surfaces.
- Control over the complexity of the mesh

are required by many appications:



- Visualisation, modelisation
  (cultural heritage, medical imaging)
- Scientific computation, finite element PDE solving
- Simulation (crash test, fluid dynamics)

Context

Geometrica research around mesh generation

- Triangulations
  - Delaunay, weighted Delaunay (in CGAL and Matlab) [Boissonnat-Devillers-Pion-Teillaud-Yvinec]
  - Periodic triangulations [Caroli-Teillaud]
  - Triangulations dD [Boissonnat-Devillers-Hornus]
- Mesh generation
  - Isotropic surface meshes [Boissonnat-Oudot]
  - Isotropic 2D and 3D meshes [Rineau-Yvinec]
  - Anisotropic meshes[Boissonnat-Wormser-Yvinec]
  - Mesh optimization [Alliez-Tournois]
  - Meshes from medical imaging [Boissonnat-Boltcheva-Yvinec]
- Surface reconstruction
  - From point sets: [Alliez-Samozino-Yvinec], [Alliez-Cohen-Steiner]
  - From cross-sections (parallel or not) : [Boissonnat-Memari]
  - From stereovision [Salman-Yvinec]

Context

Geometrica publications around mesh generation

Mesh Generation
Phd S. Oudot 05, Phd L. Rineau 07, SGP03, SMA04, GMod05, SoCG06, IPMI07, CGTA07, 2xIMR07, SGP09, MICCAI09, SGP10.

Mesh Optimization
SIGGRAPH04, SIGGRAPH05, IMR07, SIGGRAPH09, IMR09, Phd J. Tournois 09.

Anisotropic Meshes
TCS08, SoCG08, Phd C. Wormser 08.

Surface Parametrization and Remeshing
EG02, SIGGRAPH02, IMR03, SMA03, SIGGRAPH06, SGP06, TOG06, SGP08

Surface Reconstruction
EG01, CGTA02, SGP06, SoCG07, SGP07, Phd M. Samozino 07, SGP08 , ACCV09, Phd N. Salman 2010.

Mesh-based Image Segmentation
SGP06, CVPR07

CGAL : The Computational Geometry Algorithms Library

The open source CGAL project http://www.cgal.org
started in 1996, involving 8 European research institutes
and was supported by two successive European projects.

The goal of CGAL is to make the large body of geometric algorithms developed in the field of computational geometry available for research and industrial applications.

- CGAL has currently no challenger.
- CGAL is well-known for its carefull handling of robustness issues.

Why Another Mesh Generator

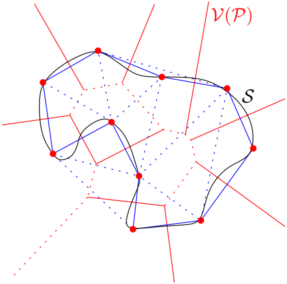
The assets of CGALmesh

CGALmesh uses the approach:
Delaunay refinement + mesh optimization,
based on Delaunay restricted triangulations,

which yields the following assets:

- Curved and planar surfaces are meshed the same way.
- Bounding surfaces and volumes or multi-volumes are meshed in a single process.
- A strict decoupling between the meshing engine and the domain oracle (queries on bounding surfaces and domain).
  This makes the mesh generator highly flexible on input domain representation:
  polyhedral domains, 3D grey-level or segmented 3D images, implicit surfaces are handled.

Restricted Delaunay triangulation

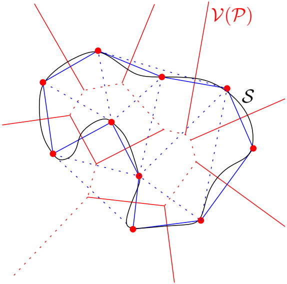


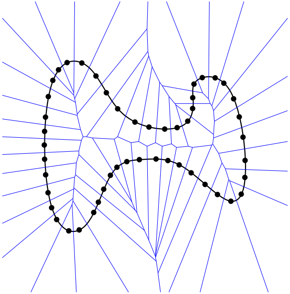
sampling P, surface S

- $\mathrm{Del}(P)$ Delaunay triangulation
- $\mathrm{Vor}(P)$ dual Voronoi diagram
  its dual Voronoi diagram
- The Delaunay triangulation restricted to S

  $\mathrm{Del}_{|S}(P)$ subcomplex of $\mathrm{Del}(P)$
  formed by faces
  whose dual intersect S

Restricted Delaunay triangulation





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  formed by faces
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[Edelsbrunner and Shah 97]
[Amenta and Bern 98]
[Boissonnat and Oudot 05]
If P is dense enough on S

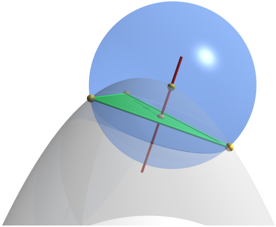
- $\mathrm{Del}_{|S}(P)$ is homeomorphic to S
- $\mathrm{Del}_{|S}(P)$ is a good approximation of S
  in term of Hausdorff distance
  normals, area and curvature estimation

Delaunay refinement meshing engine

The algorithms refines:

Bad facets: $f \in \mathrm{Del}_{|S}(P)$
– oversized (sizing field)
– badly shaped (min angle bound)
– inaccurate (distance bound)

Bad Tetrahedra : $t \in \mathrm{Del}_{|O}(P)$
– oversized (sizing field)
– badly-shaped (radius-egde ratio)

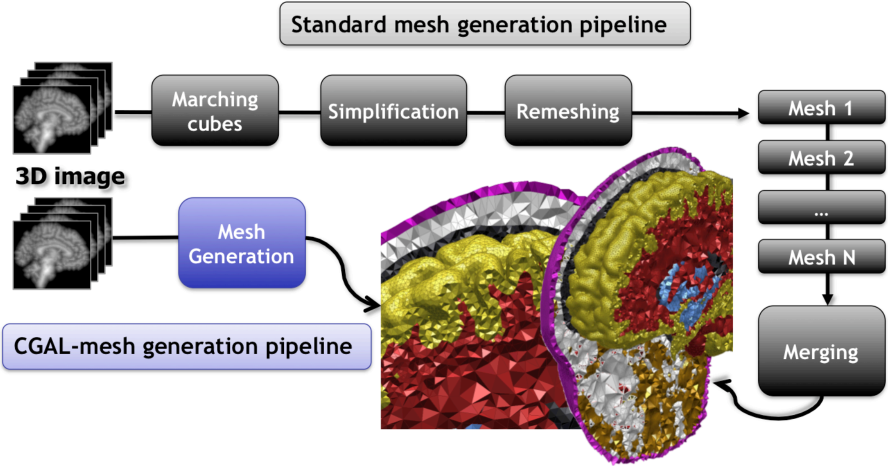


Required oracle on domain to be meshed

- point location in domain and subdomains
- intersection detection/computation between boundary surfaces and segments (Delaunay edges)

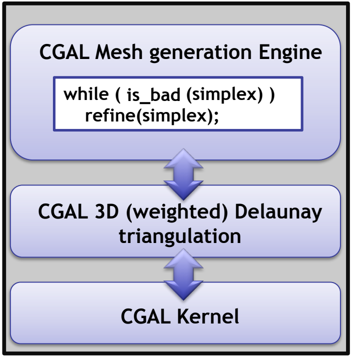
Meshing surfaces and multi-domains in a single process

CGALmesh provides a shortcut to standard pipeline



CGALmesh design

CGALmesh decouples meshing engine from domain oracle



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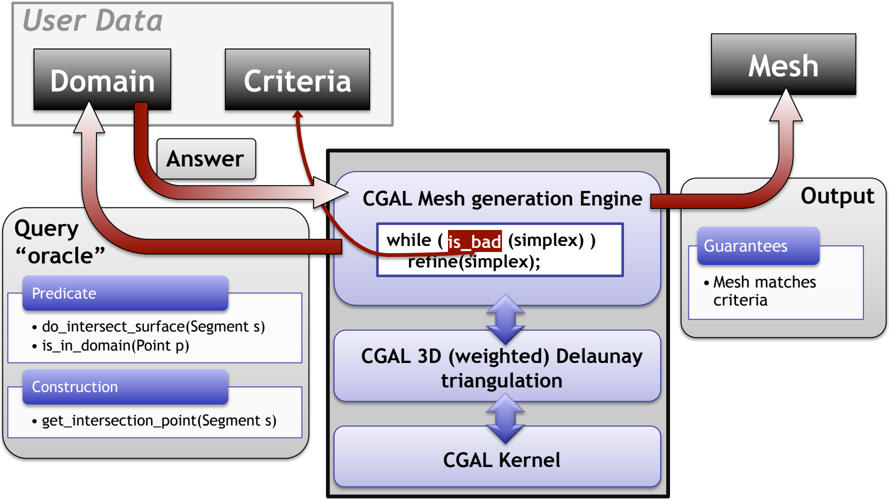
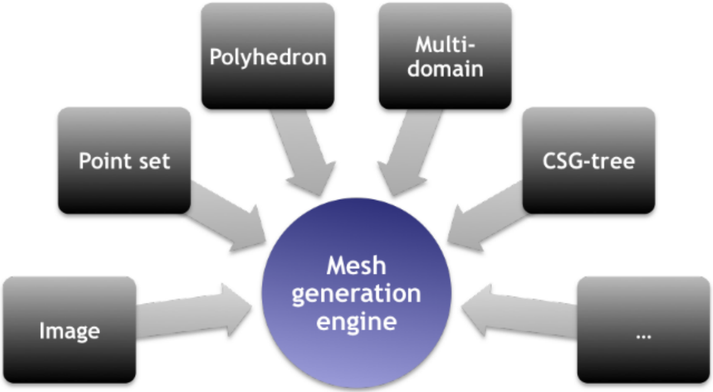


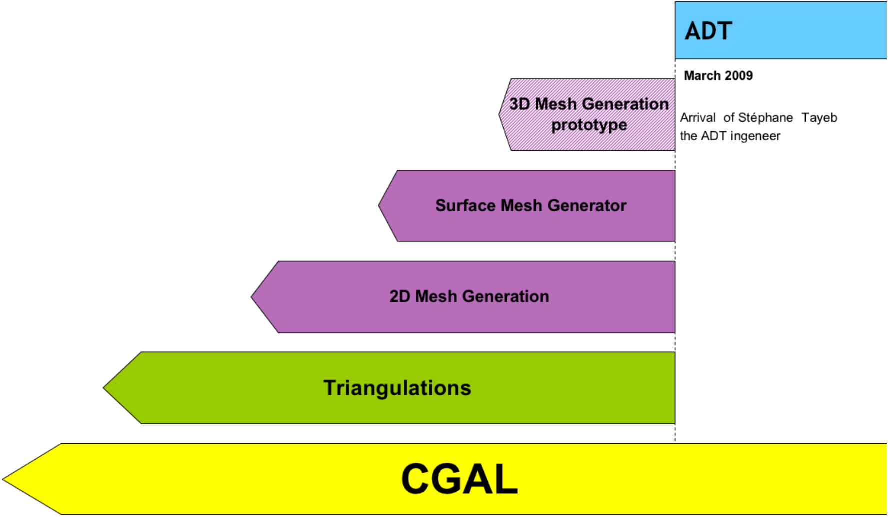
CGALmesh design

The core mesh generation algorithm is independant from input domain representation



The story board of the ADT CGALmesh

the starting point



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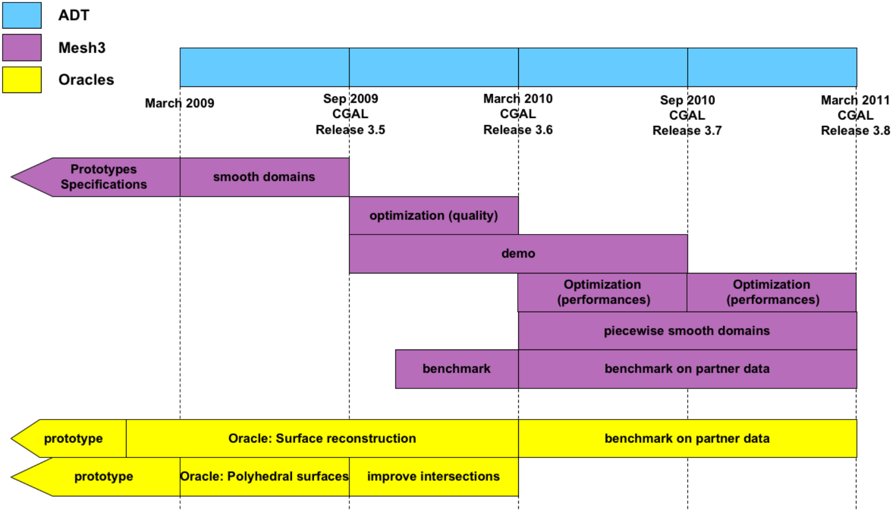
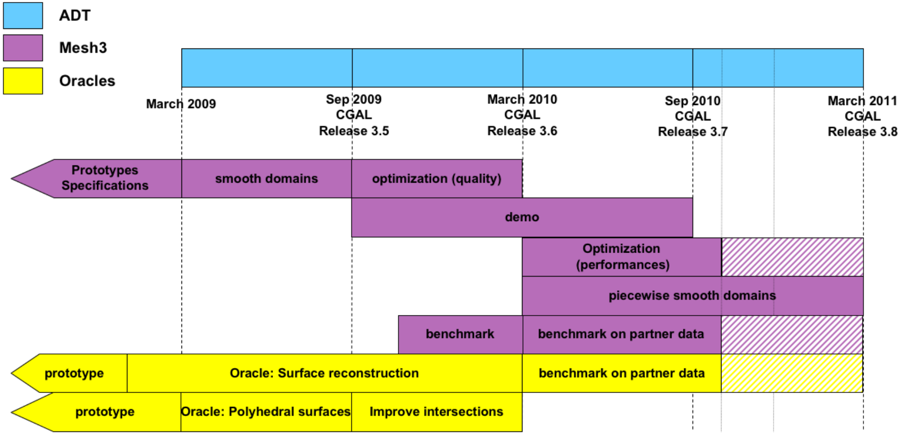


The story board of the ADT CGALmesh

The end

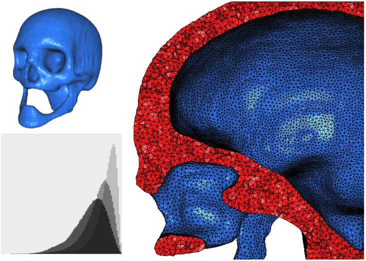


March 2009 : arrival of the ADT ingeneer Stéphane Tayeb

October 2010: early departure of Stéphane Tayeb for a new job

Summary of CGALmesh Achievements

- Topology and geometry approximation guarantees
- Control of size and shape of tetrahedra
  possibly non uniform sizing field
- Meshing multi-domains



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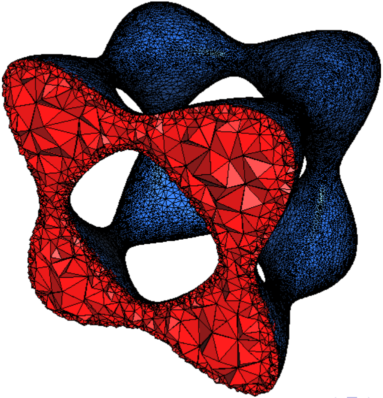

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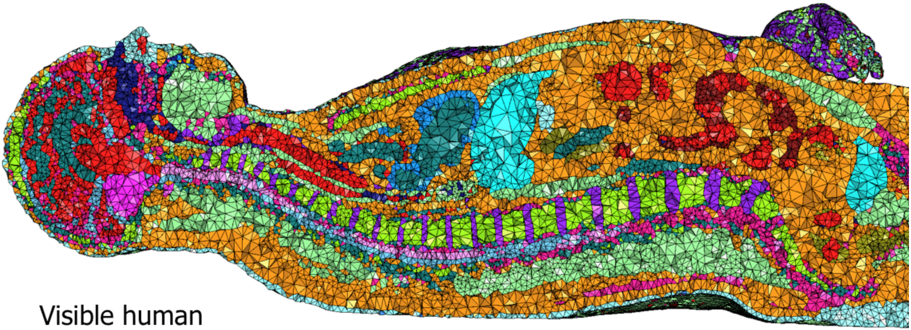
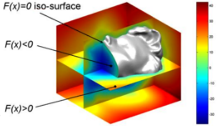


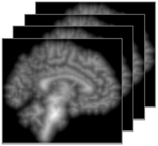
CGALmesh flexibility

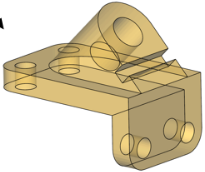
Oracles currently provided for

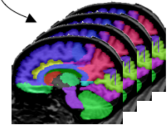
Oracles are currently provided for domains defined by :

- implicit functions
- 3D images
- polyhedral surfaces
- 3D images segmented in multi-domains
- point sets
- …







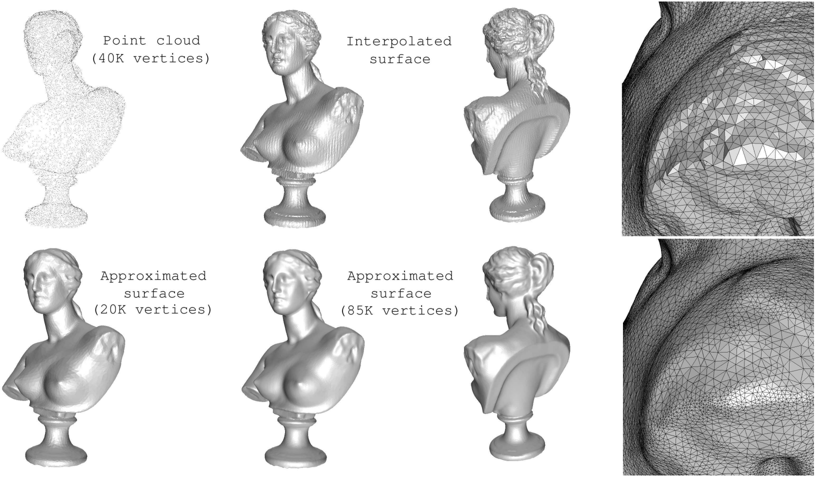


Meshing 3D domains

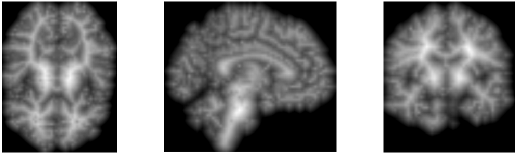
Example :a polyhedral domains

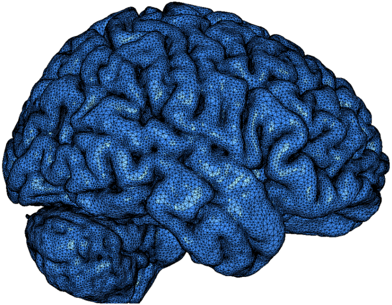
- 28K vertices
- 94K tetrahedra
- 40s mesh generation

Reconstruction from point sets



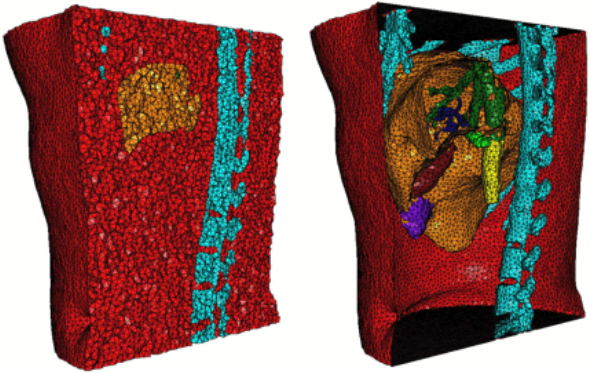
Reconstruction from 3D images





Meshing 3D multi-domains

Input from segmented 3D medical images [IRCAD]



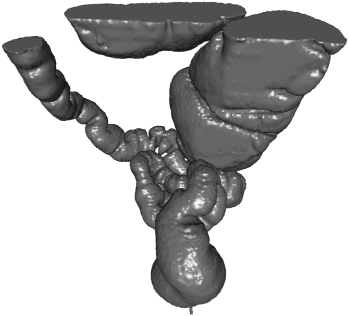
Size bound (mm)	vertices nb	facets nb	tetrahedra nb	CPU Time (s)
16	3,743	3,735	19,886	0.880
8	27,459	19,109	159,120	6.97
4	199,328	76,341	1,209,720	54.1
2	1,533,660	311,420	9,542,295	431

Meshing 3D domains

Input from segmented 3D medical images

[INSERM]

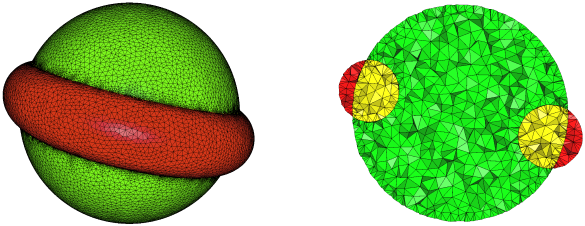
[SIEMENS]



Meshing implicitely defined multi-domains

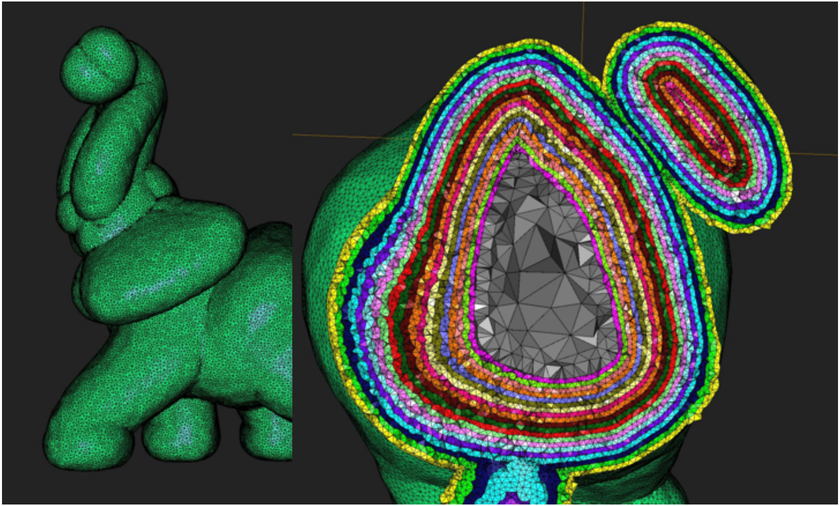
Boolean operations

- 38K vertices
- 168K tetrahedra
- 8s mesh generation time



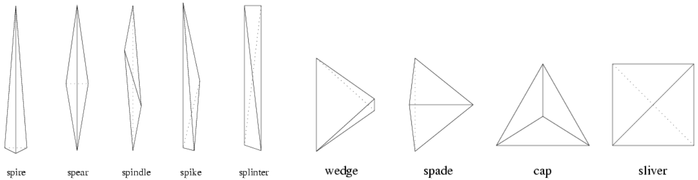
Meshing implicitely defined multi-domains

Multi-domain defined by the distance to a polyhedron



Why is optimization required ?

- Delaunay refinement provides control on:
  - Topology
  - Approximation accuracy : bounded surface-facets distance
  - Elements sizing : bound on facets and tets circumradii
  - Elements quality:
    radius-edge ratio (i.e. min angle) of facets
    radius-edge ratio of tetrahedra
- Delaunay refinement is blind to sliver
  $\longrightarrow$ no bound on dihedral angles of tetrahedra



Mesh optimization

Optimization processes in CGALmesh

4 optimization processes can be sequentially combined.

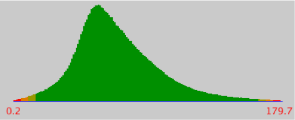
- Global optimization processes
  - Lloyd relaxation
  - ODT (Optimal Delaunay Triangulation) relaxation
- Local optimization
  - Vertex perturbation
  - Sliver exudation

Parameters of optimization processes

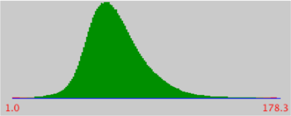
to trade computation time for mesh quality

- targeted lowed bound on dihedral angle
- time limit
- number of iterations for Lloyd and ODT relaxation
- convergence bound for Lloyd and ODT relaxation

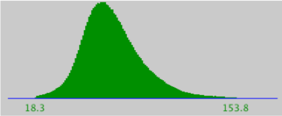
Mesh optimization



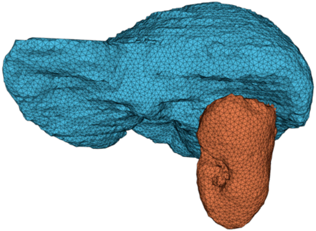
Original Mesh
(50k vertices, 290k tets, 10 seconds)

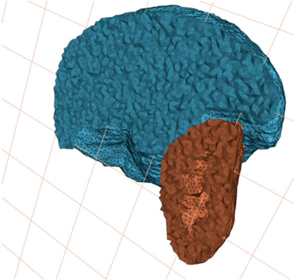


ODT smoothing
(global optimization, 110s)

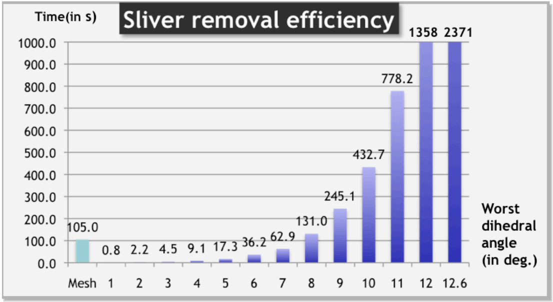


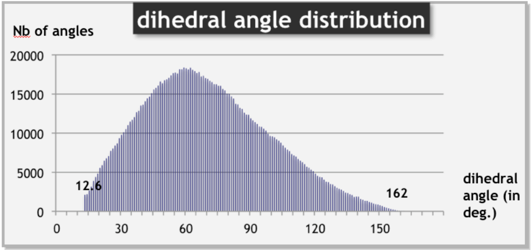
ODT + Sliver perturbation
(local optimization, 40s)





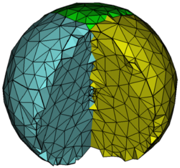
Mesh optimization





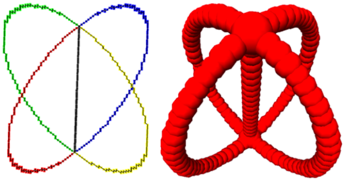
67k vertices, 225k tets, 105 s

Handling sharp features



The method of protecting balls
[Cheng, Dey et al 07]

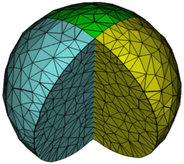
Cover sharp edges with protecting balls



- balls cover the edges
- balls do not include each other centers
- two balls centered on different edges do not intersect
- three balls do not intersect

Use a weighted Delaunay triangulation

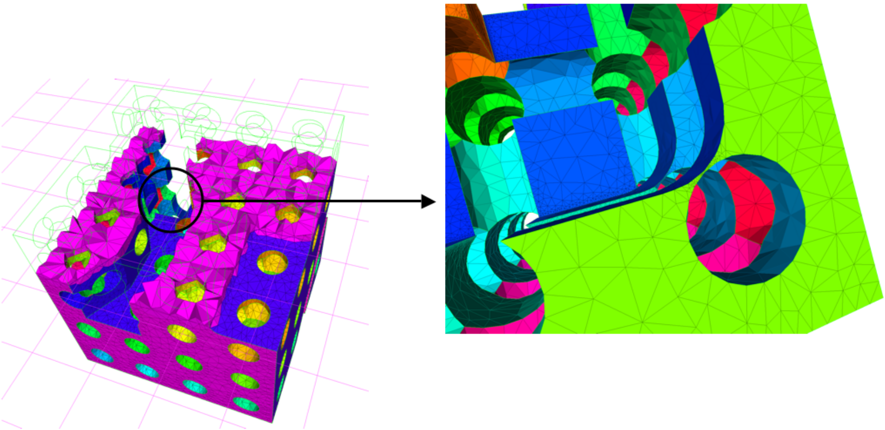
Initialize mesh with protecting balls
Run weighted version of Delaunay refinement



Segments joining centers of consecutive protecting balls are guaranteed to be edges in the mesh

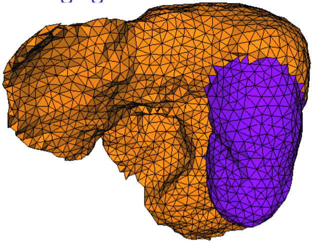
Meshing with sharp features

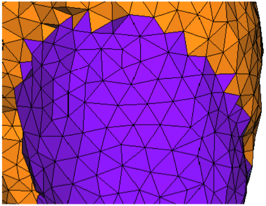
A polyhedral example

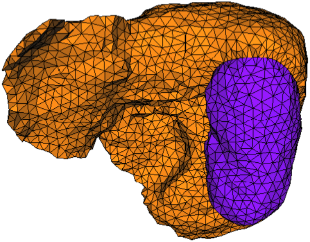


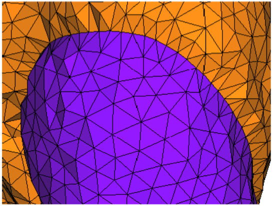
Meshing with sharp features

Example from medical imaging



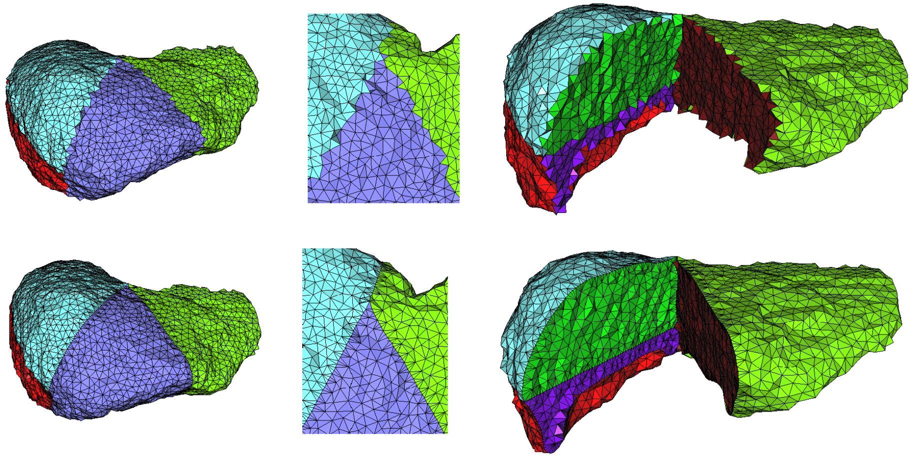






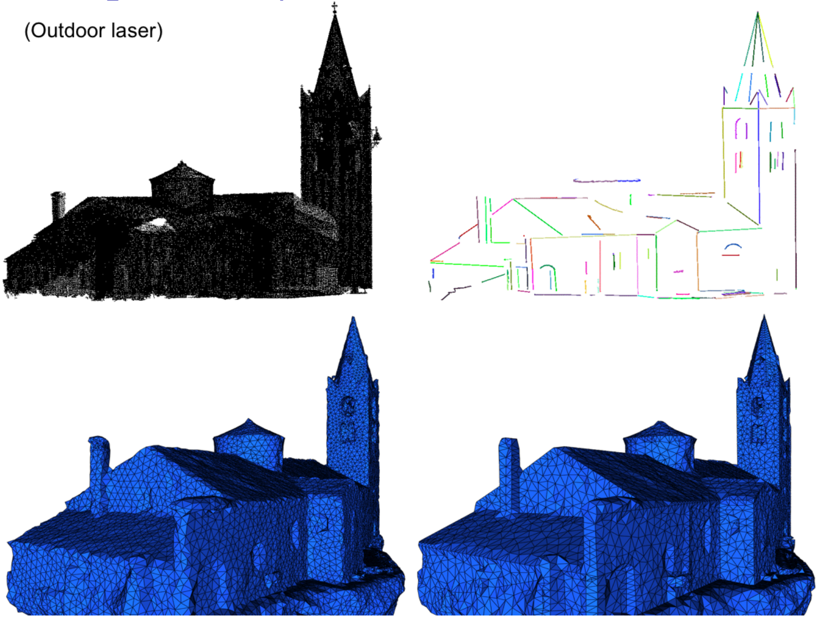
Meshing with sharp features

Example from medical imaging



Meshing with sharp features

(Outdoor laser)



Licences and users

CGALmesh licenses

- Opensource GPL + LGPL (http://www.cgal.org/)
- Commercial licenses available from Geometry Factory
  http://www.geometryfactory.com/

CGALmesh already used or in test:

INRIA	EPI Nachos, Athena, Asclepios, SOFA
Academic	CSTB, BRGM, ANR Kidpocket
Industrial	(confidential)
Alumni	More than 500 posts on the 3D mesh generator in CGAL's users mailing list

Summary

1. CGAL 3.8 the next public release of the library CGAL,
   whose outcome is scheduled in march 2011
   will offer a full fledge version of CGALmesh
   i.e. a 3D simplicial meshes generation package, handling:
   - curved surfaces
   - multi-domains
   - sharp edges
   - mesh optimization
   - various possible definition of domains to be mesh
2. Only tests and benchmarking on real data from potential users
   might suffer from some delay
   owing to the early departure of the engineer hired for the ADT.

Conclusion

Thanks for your attention

CGALmesh is available from http://wwww.cgal.org