An introduction to
MeshGems-CADSurf V1.0
A fast, robust, high quality CAD surface mesher

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A. Introduction

A.1. The MeshGems® suite

While numerical simulation has become a vital element now strongly integrated in product development cycles, the need for efficient and reliable meshing algorithms has become even stronger than ever before. Fast and realistic 3D simulations on very complex geometries have become standard in industry, pointing out the weaknesses of many meshing products on the market.

It is today mandatory to be able to transform very efficiently a real-life geometry into a mathematical representation usable by scientific simulation software. This can be achieved only if constraints such as reliability, or high mesh generation speed, can be addressed to reduce considerably the human effort necessary to exploit numerical simulation in a conception cycle.

This constant search for a reduction of costs naturally leads to considering fast and quality solutions to speed up the mesh generation step in a study.

It is for these various reasons that DISTENE and their academic research partners have been working for 20 years on automatic and reliable meshing algorithms. These are now composing the MeshGems® suite, which provides the industry with a product line for an easy and quick generation of high quality unstructured meshes.

A.2. What is MeshGems-CADSurf ?

MeshGems-CADSurf is a meshing software component which creates surface meshes automatically on top of geometries made of composite parametric surfaces defined in a CAD system, with little user interaction required. It aims at providing a very efficient and reliable surface meshing component for numerical simulations. It is the successor of BLSURF 3.1, and is the result of a long term collaboration between DISTENE and two academic research organisations, INRIA and UTT.

MeshGems-CADSurf basically requires access to some CAD query primitives, which describe the underlying geometry in any CAD system, and some user defined parameters which will drive the density and nature of the surface mesh. One can thus obtain an appropriate discrete representation of any analytical geometry. The result of MeshGems-CADSurf is an output mesh composed of connected triangles or quadrilaterals, with a density and accuracy controlled by the user.

MeshGems-CADSurf comes as a software library, which is to be plugged in a CAD/CAE software having access to a CAD kernel.

Thanks to the small and basic requirements of MeshGems-CADSurf in terms of CAD queries, it is easily usable in any CAD system. Current natively supported CAD systems include ACIS® from Spatial Inc, Parasolid® from Siemens PLM, OpenCascade® from OpenCascade, SolidWorks from Dassault Systèmes SolidWorks Corp. and others. Furthermore, thanks to the optional preconditioning module PreCAD, faulty CAD geometries can be automatically corrected prior to surface meshing.
A.3. *What MeshGems-CADSurf is not*…

MeshGems-CADSurf *is not* intended to be a general purpose end-user meshing software. In particular it does not have a GUI, and it does not read CAD files directly. However MeshGems-CADSurf queries CAD kernels in order to generate surface meshes, and proposes a preconditioner to facilitate meshing. This preconditioner prepares the data and can rebuild the topology for meshing, but it is not capable of outputting a clean or healed geometry on file.

MeshGems-CADSurf is solely a surface mesher, and it does not generate volume meshes. It does not correct missing Boolean operations either. However, the MeshGems suite offers other components for these needs, such as:

- **MeshGems-Cleaner**, which heals surface meshes by removing self-intersections, gaps, holes, non-conformities, badly shaped elements, etc., even if this can alter locally and in a limited way the geometry,

- **MeshGems-Tetra**, which is capable of very robustly filling volumes defined by a closed surface mesh with high quality tetrahedral,

- **MeshGems-Hexa**, which is capable of generating pure hexahedral meshes on geometries defined by a closed surface mesh.

B. *Overview of MeshGems-CADSurf V1.0*

MeshGems-CADSurf is a surface mesher based on a coupled Delaunay/front-advancing method and anisotropic meshing. It comes as a dynamic library with a stable yet evolutive Application Programming Interface (API). As such, all previous implementations using MeshGems-CADSurf are fully compatible with the latest release. All previous features are kept in this latest release, including:

- Automatic generation of triangles and quadrilateral meshes directly from CAD, without the need for an intermediate meshing of boundaries
- Curvature driven or size driven meshing, gradation
- Patch independency (also known as “cross-patch” meshing)
- Isotropic or anisotropic meshing
- Periodic meshing
- User defined forced discrete entities
- Use of the preconditioning library (PreCAD) for CAD topology reconstruction and cleaning prior to surface meshing.

C. *What’s new with respect to the previous version?*

The release 1.0 of MeshGems-CADSurf includes several significant new features compared to BLSURF 3.1. The main one are presented here.

C.1. *Quadratic meshing*

The release 1.0 of MeshGems-CADSurf includes a quadratic meshing capability, available with all meshing options. The use of quadratic meshing is expanding today out of the traditional usage made by Finite Element Analysis in structure mechanics. Surfaces with curvatures can indeed be approximated with better accuracy thanks to a quadratic approximation, while keeping the element count low.
**MeshGems-CADSurf** can create highly accurate quadratic surface meshes, while preserving good computational properties. The choice of mid-nodes is indeed made so as to improve the positivity of the elements Jacobians, which is an essential requirement from computational solvers.

As are all developments, the quadratic meshing feature is fully compatible with the PreCAD module.

Comparison between linear and quadratic discretizations: the discretizations above were computed with **MeshGems-CADSurf** with a similar number of vertices. We show above the corresponding meshes computed by **MeshGems-CADSurf** (top), and the corresponding discretized geometries (bottom).
We show above the effects of MeshGems-CADSurf's specific processing to improve the Jacobians. MeshGems-CADSurf moves quadratic mid-nodes along the surface so as to improve the positiveness of the elements Jacobians.

C.2. Automatic correction for volume preservation

A new outstanding feature of MeshGems-CADSurf is its ability to detect and to prevent self intersections automatically in the geometry before they actually occur, as they may in cases of very coarse discretisations of curved areas in close surfaces. This ensures that these issues will be corrected prior to any consequent volume meshing. An example of such situations is shown below:
D. The features of MeshGems-CADSurf V1.0

As a generic CAD surface mesh generator, MeshGems-CADSurf is capable of addressing several kinds of applications: triangular or quadrilateral meshing, CAD correction, patch independency, coarse anisotropic meshes, etc.. In all cases, MeshGems-CADSurf places the vertices onto the original CAD surface, so as to ensure that the triangulation indeed corresponds exactly to the input geometry. Furthermore, modifications are tracked and returned to the hosting applications to ensure associativity.

We highlight below some of its main features.

D.1. CAD preconditioning prior to meshing

The seamless integration of cutting edge parametric surface meshers in all major CAD engines, which all have their own specificities and differing internal data representations, requires a robust and versatile compatibility layer. Moreover, a large number of meshing failures are caused by incorrect CAD data, which often derive from translations errors (exporting and importing between CAD products, translating from one format to another…) or even from limitations inside CAD kernels.

This is for this purpose that the PreCAD preconditioning module was designed. It comes as a middleware between the native CAD system used by the hosting application, and MeshGems-CADSurf. It automatically and seamlessly integrates into the meshing process.

PreCAD’s cleaning capabilities combine several assets: they are fully automatic (no need for an “epsilon” precision parameter for example), easy to drive, reliable, flexible, and very fast.

It addresses both manifold or non manifold geometries. It aims at addressing a number of issues, including:

- Missing or erroneous topological information: it can recompute a correct topology of patches, preventing non conformal meshes;
- open patches in UV parameter space (closed or periodic surfaces), or with a degenerated or incomplete parameterization;
• micro curves elimination and correction of misfit or missing curves;
• optimization of small curves through merging.

The usage of PreCAD is quite simple. Instead of calling the CAD kernel directly, one has just to call PreCAD instead, which will then in turn query the CAD engine, while correcting the errors on the fly!

We show below an example of PreCAD effects on a given geometry:

Mesh generated without PreCAD: some patches have incorrect definitions and fail to mesh, poor CAD translator used leads to curves being split into smaller entities…

Mesh generated with PreCAD: all patches mesh successfully and translator artefacts are corrected to revert to original curves.

D.2. CAD surface meshing for scientific computing

MeshGems-CADSurf provides many controls and features to generate both triangular or quadrilateral meshes, we highlight below some of its assets.

D.2.1. Associativity

When one makes computations out of CAD data, it is mandatory to preserve an essential information: the CAD associativity. Associativity keeps indeed the link between the numerical simulation and the design information. MeshGems-CADSurf makes sure that the proper information and potential modifications are tracked and returned to the hosting applications, ensuring that the associativity remains tight throughout the meshing process.

D.2.2. Size and gradation control

MeshGems-CADSurf can be controlled through several ways, and these controls can be local or global, and can be mixed. These can be:

- **element size based**: one can provide the expected size of elements, a so called “physical” size
- **curvature based**: the density is then controlled by the curvature: the smaller the local curvature radius is, the denser the mesh becomes. The curvature accuracy itself can be controlled by the geometrical approximation, or by the chordal error (“tolerance”), or a combination of both:
  - the chordal error / tolerance determines the maximum desired distance between a triangle and its supporting CAD surface;
  - the geometrical approximation controls the limiting angle between the plane of a triangle of the mesh and each of the tangent planes at the three vertices of this triangle
Together with this, one can also control the gradation, which represents the maximum ratio between the lengths of two adjacent edges. A control of the global minimal and maximal size of elements is possible too.

Note that this control can be used to generate “visualization” meshes, eg, meshes with a very small element count which preserve the geometry.

- *sizemap based*: the control is local through user defined sizemap functions

We show an example with effects of various global density controls in the picture below. Note that local control is also possible (for example, one can specify a local tolerance, a maximal or minimum size of elements, or other parameters on a given CAD entity - curve or surface -)

Control of size of elements: all elements have the same size if geometry allows it, but curved areas maybe not be very accurate

Curvature based size control, without gradation: the higher the curvature, the denser the mesh becomes. The mesh gets very coarse in flat areas.

Curvature based size control, with gradation: the density is driven by the curvature, but also by the growth rate between an element and its neighbours.

Combination of curvature control, size of elements and gradation.

D.2.3. Some examples

We show below some examples of typical applications of MeshGems-CADSurf meshing, extracted from the validation suite.
Quadrilateral meshing with constant size

- 1555 CAD surface patches
- constant size required (2% of bounding box)
- 31524 quadrilaterals, 1450 triangles
- CAD processing and meshing in 3 seconds (614k elements/mn)

Triangular meshing with constant size

- 3648 CAD surface patches
- constant size required (2% of bounding box)
- 70558 triangles
- CAD processing and meshing in 6 seconds (700k elements/mn)
- 3202 CAD surface patches
- constant size required (4% of bounding box)
- 19 178 quadratic triangles (37 607 vertices)
- CAD processing and meshing in 4 seconds (287k quadratic elements/mn)

Quadratic triangular meshing controlled by curvature and global size, with Jacobian correction
D.2.4. specific features

We describe here some specific capabilities of **MeshGems-CADSurf**

### D.2.4.1. Patch independent meshing and quality control

Typical industrial CAD structures contain a huge amount of CAD surfaces, many of which are very small if not ridiculously tiny, resulting from various CAD boolean operations, translations or corrections. Since these entities are also supporting physical attributes, it is often mandatory to respect their exact structure when it comes to meshing them. This may lead unfortunately to very small or very narrow elements, conflicting with their expected user-defined size, which in turn become a problem for the simulation itself.

Fortunately, there is a way to get round this problem: the use of patch independent (or “cross patch”) meshing. This allows the mesher to cross the boundaries of patches whenever the continuity allows it, on patches selected automatically or manually by the user. With this method, the vertices will all be located on the original CAD, but some elements may cross the boundaries in order to be better shaped.

This feature is illustrated below:

Mesh generated without patch independency: some very narrow patches induce very sharp edge elements

Mesh generated with patch independency activated: the elements are all much regular

**MeshGems-CADSurf** offers several controls to allow the user to promote quality of elements over geometry accuracy. One of them is to detect and remove slivers, which are usually caused by strong geometry constraints.

### D.2.4.2. Periodic meshing

This feature allows MeshGems-CADSurf to build meshes so that patches which define a periodic boundary condition are meshed identically (actually, the mesh of one of the periodic faces is copied to the other face, using the same transformation which transforms one face to the other). This is particularly useful when computational domains use symmetry (or translations, or...
rotations, or combination of these) to reduce the size of the problem, by isolating a representative portion of the full domain. As are all developments, the periodic meshing feature is compatible with the PreCAD module.

![Example of two periodic meshed faces (quadrilateral meshing)](image1)
![Same example, but with three periodic meshed faces in convolution (triangular meshing)](image2)

**D.2.4.3. Anisotropic meshing**

Another significant feature is the capability to generate anisotropic meshes in curved areas, with a stretch factor defined by the user at runtime. This is particularly useful to capture the geometry very well in high curvature areas while ensuring a very small cell count. Moreover, the stretch coefficient can be adjusted so as to be compatible with solver requirements.

![An example of anisotropic mesh produced by MeshGems-CADSurf](image3)
E. MeshGems-CADSurf, a software product of industrial quality

E.1. Application Programming Interface (API)

MeshGems-CADSurf offers a comprehensive and stable API, which allows integrators to exploit fully and simply all the features supported. This API is fully described in the user documentation.

E.2. Native support of CAD engines

MeshGems-CADSurf only uses basic query functions, common to almost all CAD engines, to access the geometry. These are:
- Operators from the parametric space to the real space (for both curves and surfaces)
- First and second order derivatives

As such, MeshGems-CADSurf is totally independent from any specific CAD engine. It is delivered without any complex bundle to third party CAD engines, and does not have a dependency to a specific version of these. Also, the PreCAD module is capable of correcting potential defects of CAD engines.

The source code of the native interfaces between MeshGems-CADSurf and various third party CAD engines is delivered along MeshGems-CADSurf. These native interfaces include, but are not limited to:
- ACIS® from Spatial Inc,
- Parasolid® from Siemens PLM,
- OpenCascade® from OpenCascade.

Since the functions required are few and quite basic, it is not complex to integrate MeshGems-CADSurf with any given CAD engine.

E.3. Reliability

A comprehensive validation suite has been built over the years for MeshGems-CADSurf, which contains about 3,000 geometries. These geometries come from various horizons and applications, almost all of them describing complex cases, and representing a total number of surface patches well over 3 billion. All these test cases are run, and each for several meshing configurations, to verify the reliability of a given software version, as well as to assess its speed, efficiency and mesh quality.

These geometries of various origins are stored in several file formats: IGES, STEP, SAT, X_T, BREP, CATPART, PRT, etc.

MeshGems-CADSurf’s validation suite: distribution of geometry complexity
### E.4. Speed and quality

Depending on the options, the size of the input triangulation and the hardware, one can reasonably expect to complete MeshGems-CADSurf on a PC in about a minute.

We show below some test cases and the corresponding measurements obtained when running MeshGems-CADSurf. The geometries use various formats (IGES, STEP, SAT; X_T…).

The table illustrates:

- The total number of CAD surface patches
- The meshing time (in seconds). This accounts for both the meshing time and the CAD preconditioning. The size control is a combination of curvature-driven density control (20° geometrical approximation), global size (1% of bounding box), and gradation (1.3). Optimization is activated.

Note that when a constant size is required, the speed may be up to twice as fast.

The hardware used is a PC equipped with Intel I7-2600s@2.8GHz (one core used)

- The number of triangles generated
- The speed (in number of elements per minute)
- The quality of triangles

<table>
<thead>
<tr>
<th>Test case</th>
<th>number of patches</th>
<th>meshing time in seconds (including PreCAD processing)</th>
<th>number of triangles</th>
<th>speed (elts/mn)</th>
<th>Quality (1)</th>
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<td>12309-wheel</td>
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<tr>
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</table>

\[ Q_K = \frac{h_{\text{max}}}{\rho_k} \]

\( h_{\text{max}} \) being K’s longest edge, \( \rho_k \) the inradius of K, and \( \alpha \) is a normalisation coefficient chosen so that the quality of the equilateral triangle is 1.

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1. The quality of an element K used here is computed as \( Q_K = \frac{h_{\text{max}}}{\rho_k} \), with \( h_{\text{max}} \) being K’s longest edge, \( \rho_k \) the inradius of K, and \( \alpha \) is a normalisation coefficient chosen so that the quality of the equilateral triangle is 1.
MeshGems-CADSurf’s speed on some test cases (pictures below)

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Speed (s)</th>
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<td>12611-cylinder_head</td>
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<tr>
<td>12599-shock_absorber</td>
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</tr>
<tr>
<td>10196-scaffolding</td>
<td>4</td>
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</tbody>
</table>

The diagrams below illustrate the mesh models of 11708-Modem and 12251-actuator.
E.5. Platforms

MeshGems-CADSurf and its companion module PreCAD are available as dynamic libraries on these operating systems:

- Windows (2000, XP, Vista, Seven, 32 bit or 64 bit operating systems),
- Windows (2000, XP, Vista, Seven, 32 bit or 64 bit operating systems),
- Linux (32 bit and 64 bit operating systems),
- Linux (32 bit and 64 bit operating systems).

Other operating systems are also available on demand.

F. Ongoing R&D

Several topics of interest are currently being investigated for surface remeshing. These include:

- Optimising the code for better performance.
- Maximising quad count in mixed tri/quad meshing
- Take into account volume proximity to control mesh size. A similar approach is already implemented to prevent and correct self intersections, but the goal is to control the density to ensure optimal tetrahedral quality in the volume meshing step.

This last topic is illustrated below, where we activated the volume proximity to improve the tetrahedral mesh quality. This feature can naturally be coupled with all other MeshGems-CADSurf features, like for instance periodic meshing.
Volume proximity activated together with periodic meshing (all surfaces are periodic two by two with the opposite face).

Volume proximity can be coupled to other features, like here with periodicity.

Volume proximity detection induces a denser mesh where surfaces get close to each other, ensuring a better quality of corresponding tetrahedra.