MeshKit: An Open-Source Toolkit for Mesh Generation

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Outline

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- The Meshing Problem(s)
- A Graph-Based Approach
- MeshKit Classes
- Examples
Motivation

- How do we view the forest (as opposed to the trees) of mesh generation?
  - At first glance, the meshing process follows a topological model, i.e. geometric topology
  - If you look further, though, it’s a bit more general than that, more akin to a graph-based model (of which a topology is a special case)

- Other things are pretty important when you start looking into the trees, too
  - Infrastructure, especially for geometry-based meshing
  - Availability of a stable of basic meshing capabilities (edge/tri/tet meshers, smoothing, refinement, visualization, quality analysis, ...)

- Developing a meshing library is not a new idea (Netgen, gmsh, tetgen, CAMAL, ...)
  - However, writing a meshing library that supports interoperability is
    - Interoperability in mesh database, geometric model, best-in-class tools and algorithms from various sources

- We need a meshing library that supports needs of two communities
  - Users, so they can generate meshes
  - Developers, so they can start developing specific algorithms right away, instead of after they spend a few years on a good infrastructure

- Open source model more important in meshing than in other areas
  - No matter how good the tool, you’ll always reach a point where it doesn’t work for your problem
  - Sometimes it’s a matter of one key capability that’s special to your problem, with the other 95% of your problem treated by existing tools
Other Meshing Libraries

- **CAMAL 5.1 (SNL)**
  - License: proprietary, for research or US Gov’t work
  - Algorithms for tri, quad, tet, hex (sweep, map, submap)
  - Geometric evaluation by application-provided implementations of abstract classes CMLCurveEval and CMLSurfEval
  - API in terms of node positions & connectivity, no high-level “mesh” datatypes
    - No support for assembling bounding mesh from geometry

- **Gmsh**
  - License: GPL
  - Algorithms for tri, quad (recombine), tet, hex (extrude)
  - Reconstruction of parametric space for disk and non-disk surfaces, using harmonic maps
  - Direct links to OCC-based geometry

- **VTK, SciRUN, Salome**
  - Frameworks that include meshing, along with lots of other stuff
  - Tend to be all or nothing

- **In general, difficult to mix and match algorithms from different sources**
  - Especially when considering geometric model and use of higher-level API for mesh
The Meshing Problem(s)

- Geometry-based meshing
  - Mesh vertices
  - Mesh edges
  - Mesh surfaces
  - Mesh volume

- Sweep dependencies
The Meshing Problem(s)

- Mesh Copy/Move/Merge
- Watertight models

- Mesh-Based Geometry
- Embedded Boundary Meshing
Graph-Based Organization of Meshing Problem

- Explicitly drive meshing as a graph-based process, with nodes as operations and edges as dependencies
  - More flexible, can express wider variety of complex, mesh-related operations
  - Explicit representation of meshing dependencies allows parallelization of the process
  - May facilitate updating the mesh after small changes

- Various types of graph nodes
  - Meshing algorithm applied to one geometric entity
  - One algorithm applied to a collection of entities
    - VertexMesh, EdgeMesher
  - Mesh-based operation applied to results of preceding operation
    - Mesh, then smooth, then refine

- However, be careful about graph complexity seen by users
  - These graphs can get complicated, fast
  - Support automatic construction of graph nodes, based on constraints from specific meshing algorithms
    - E.g. tet mesher needs surfaces meshed with tris

- 2 phases of graph execution
  - Setup, where algorithms express their requirements (possibly by constructing more nodes)
  - Execute, where mesh gets generated or operation gets performed
Example of Graph-Based Mesh Generation

- Directed graph, with single (trivial) root, leaf nodes
- Executed in two phases:
  - **Setup**: Topological-sort traversal from leaf to root, possibly adding (or moving) nodes upstream
  - **Execute**: Topological-sort traversal from root to leaf
- Example: tri-mesh a surface

![Diagram of graph-based mesh generation](image)
More Complicated Example: Sweep-Mesh a Volume
MeshKit Core Classes

- **MKCore**
  - MeshKit instance class
  - isA graph, hasA (single) root, leaf nodes of graph
  - Keeps references to geometry, mesh, relations interface instances

- **ModelEnt**
  - Geometric model entity, mesh set handles
  - Limited set of commonly needed functions, e.g. geometry evaluation, topology traversal
  - In traditional meshing, corresponds to (CAD) geometry entity
    - In other cases, e.g. mesh copy/move, no corresponding CAD entity
  - MEntSelection: std::map<ModelEnt*, moab::Range>
    - Used to store tuples of model entities and mesh generated for those model entities by containing MeshOp
  - MeshedState: NO_MESH, BOUNDARY_MESH, SOME_MESH, COMPLETE_MESH, Refined_MESH, POST_MESH

- **MeshOp**
  - isA graph node
  - Keeps a map<ModelEnt*, moab::Range>, to store mesh generated or operated on by this MeshOp
  - Can mesh multiple entities with one MeshOp instance
    - Fewer graph nodes
  - Or, separate instances of a given MeshOp
    - E.g. if different input needed
Dynamic Registration of MeshOps

- MeshKit is meant to support *both* mesh generation users, and mesh generation developers
  - Need to support dynamic registration of new MeshOp classes
- Would like to enable both requesting MeshOps by name, or automated construction based on ability to mesh a given ModelEnt or produce a given mesh entity type
- Accomplish this by requiring a specific set of functions for a MeshOp, and registering the MeshOp with MKCore
- These MeshOp functions need to be defined:
  - Constructor with arg list (MKCore *, MEntVector &)
  - static const char *name() – name by which this MeshOp is requested
  - static const moab::EntityType* output_types() – array of mesh entity types produced / operated on by this MeshOp (terminated by moab::MBMAXTYPE)
  - static bool can_mesh(iBase_EntityType dimension) – returns true if the MeshOp can mesh model entities of this dimension
  - bool can_mesh(ModelEnt* ent) – returns true if this MeshOp can mesh the *specified* entity
MeshOp Registration, Construction

- Tried really hard for static registration from each MeshOp’s compilation unit
- But, for static library case, if the new MeshOp isn’t mentioned by name directly or indirectly from an application, it wouldn’t get pulled in from library at link time
  - Instead, calls to register MK-native MeshOps are put in a few static functions, which are referenced from MKCore
  - Application-defined MeshOps can be registered from main, or from any function linked into final application
- To register a MeshOp: create a global proxy object using:
  ```
  #include "meshkit/RegisterMeshOp.hpp"
  RegisterMeshOp<MyMesher> MyMesher_GLOBAL_PROXY;
  - Proxy object registered with MeshOpSet singleton accessed through MKCore
  - This object should persist throughout program execution
- Once registered, a new MeshOp can be constructed by name:
  ```
  mk->get_entities_by_dimension(1, curves);
  MyMesher *mm = (MyMesher*) mk->construct_meshop("MyMesher", curves);```
MeshOp setup_this(), execute_this() functions

- **setup_this()**
  - Creates graph nodes that represent prerequisites, e.g. for surface mesher, mesh the boundary; that is, it “sets up” the meshing process for entity(ies)
  - For trivial or automatic cases, can call MeshOp::setup_boundary()
    - Automatic: use default scheme for dimension, which is 1st MeshOp type for that dimension registered in MKCore
  - This function often results in new MeshOps getting created, and put in the graph upstream of the current MeshOp
  - For more complicated situations, e.g. automatic scheme selection, this may involve deeper changes to the graph
    - Needs more study

- **execute_this()**
  - Is where the typical mesh generation or mesh-based operation happens
  - If setup was done properly, all prerequisites will be satisfied by the time this is called
  - Most put generated mesh into MeshOp::MEntSelection (map<ModelEnt*, moab::Range>)
    - Provides some reversibility
    - At this point, don’t intend to store extra data, e.g. new vertex positions, so not completely reversible

- **MKCore, MeshOp both implement setup(), execute(), which just perform the setup and execute traversals from leaf/root (MKCore) or current node (MeshOp)**
Example MeshOp: EdgeMesher

- **setup_this():**

  ```cpp
  for (MEntSelection::iterator mit = mentSelection.begin();
     mit != mentSelection.end(); mit++) {
    ModelEnt *me = mit->first;
    // check if already meshed, and return if so
    if (me->get_meshed_state() >= COMPLETE_MESH ||
        me->mesh_intervals() > 0) continue;
    // check/compute the intervals for this ModelEnt
    check_intervals(me);
  }
  // assign bounding vertices to VertexMesher
  setup_boundary();
  ```

- **execute_this():**
  - Typical parametric-space edge meshing
  - Equal, bias, dual (bias), and curvature options
Example MeshOp: CAMALPaver

- (see src/extern/CAMAL/CAMALPaver.cpp)
External Libraries

- Important to support both OSS and non-open libraries/algorithms
- General rule: if library/algorithm is LGPL or compatible, will bundle that code with MeshKit
  - Netgen (tri, tet)
  - Qslim1.0 (decimation)
  - Mesquite (smoothing)
  - Verdict (mesh quality)
  - LEMON (graph)
- Otherwise, support through wrappers enabled by configure-time option
  - CAMAL (SNL)
  - Gmsh (GPL)
  - Other
Other Details

- Graph functionality imported from Lemon graph library
  - Like Boost Graph Library, but with fewer templates-on-templates
  - Right now, accessing graph through mix of methods on MeshKit classes and direct calling of Lemon functions on graph + nodes/edges returned from those classes
    - Probably better to make a GraphNode class in MeshKit core, put all graph-accessing functions and members there
  - Right now, only MeshOps can be graph nodes
    - Eventually, probably need others, e.g. maybe ModelEnt should also be derived from GraphNode

- That pesky interface question
  - Geometry and relations accessed through iGeom, iRel
  - For mesh, access through MOAB or iMesh interfaces
    - iMesh and MOAB instances both available from MKCore
    - Will require implementing MOAB interface on top of iMesh, to support interoperability with other mesh databases; sounds complicated, but this is an important part of MeshKit’s scope
Other Details (2)

- Scripting
  - Eventually, will have Python interfaces generated automatically
  - It’s been recommended to me that we also bundle a Python interpreter directly with MeshKit; sounds like a good idea, at least for some apps

- Documentation extremely important
  - Everything in MeshKit should be born (and probably conceived) documented
  - Will use doxygen almost exclusively for documentation
    - It can do more than most people realize
Algorithms Available in MeshKit 0.9...

Copy/Move/
Merge/Extrude

JaalQuad

SCDMesh

EBMesh
Algorithms Available in MeshKit 0.9...

- Qslim (Decimate)
- Facet-Based Surface
- CAMALPaver

- CAMALTriAdvance
- CAMALTetMesher
- NGTetMesher (Netgen)
- OneToOneSwept
- MesquiteSmooth
- EdgeMesher
- VertexMesher
- (others)
Future Plans

- Native tri mesher (Triangle? Netgen? Home-grown?)
- Tri, tet, hex (parallel) refinement
- Parallel mesh merge
- Auto-generated Python interfaces
- Interval matching
- More work on graph-based approach
Conclusions

- Need an open-source mesh generation environment, that
  - Supports both users and developers
  - Has bridges to non-open-source meshing algorithms
  - Is flexible in how various algorithms interact

- Graph-based meshing process captures many of the relevant workflows in mesh generation

- MeshKit designed to support these uses

- V0.9 (almost) ready (targeting mid-April release)

- Meshkit-announce (https://lists.mcs.anl.gov/mailman/listinfo/meshkit-announce) for details
Copy/Move/Merge/Extrude

- CopyMesh, ExtrudeMesh, MergeMesh
- Works with any type of 2D, 3D elements
- 15mins start to finish for 12M element hex mesh (Linux desktop workstation)
  - Geometry construction
  - Assembly meshing
  - Copy/move/merge

- Boundary conditions, material definitions handled using set abstractions:
  - Copy set: new set with entity copies
  - Expand set: entity copies added to same set
  - Extrude set: entities replaced with (d+1)-dimensional extrusions

- Allows handling of various set types with a common abstraction
- Will work similarly for refinement
- F, C: expand sets
- V1: copy set
- Side: extrude set
Jaal QuadMesher

- Tri-quad conversion using deterministic tree matching algorithm
- Cleanup: local (singlet, doublet, diamond removal), global (Bunin's algorithm)
- Provable robustness, with very few irregular nodes in final mesh
- Currently, 20k quadrilaterals/sec (~2.4GHz Linux workstation)

5658 nodes, 10669 triangles
5192 nodes, 4868 quads
Structured Background Mesher (SCDMesh)

- Generates a structured Cartesian grid using a geometric entity's bounding box
- Adjustable or equal spacing
- Supports EBMesh, and basic structured mesh generation
Embedded Boundary Mesh Generation (EBMesh)

- Find inside/boundary/outside elements in Cartesian mesh surrounding a body
- Uses fast, robust ray tracing based on hierarchical OBBs in MOAB
- 10x faster than Cart3D
- Uses SCDMesh
Decimation (Qslim)

- Surface mesh decimation based on Qslim1.0 (Garland, UIUC)
- Main method of decimation: Edge Contraction
- Minimize certain error (quadrics)

10 million triangles high resolution

20 k triangles

Before

After

contract
Facet-Based Geometry (FBiGeom)

- C1-continuous facet-based geometric representation (Owen et al., ’02), implemented in MOAB
- FBiGeom provides limited iGeom API based on smooth facet-based geometry
- 2 options: linear or smooth evaluations

20 k triangles