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Research Note

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A Practical Approach to Challenges in Meshing Mining Models

Edward Dzik[a,*], Christine Detournay[a], Peter Cundall[a]

[a]*Itasca Consulting Group, Inc., 111 Third Avenue South, Suite 450, Minneapolis, Minnesota, 55401, USA*

Abstract

A practical approach to overcome challenges to the generation of 3D surface and volume meshes encountered in geological settings is presented. Input data can be delivered in a variety of forms from a mine: laser-scanned point clouds, facet-based surfaces, contour lines, and less commonly mathematical boundary representations. In addition to delimiting different geological materials and excavations, the data often includes descriptions of discontinuities such as faults and joints, which may completely or partially cut through each other and the various geological domains and excavations. Meshing this geometry proves extremely challenging, not only because it is non-manifold, often requires meshing at vastly different scales, but also raw data delivered from a mining client is typically not clean. Several custom meshing tools have been developed by Itasca as plug-ins to a commercial CAD system that greatly facilitate the mesh generation process for geological settings.

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Keywords: unstructured mesh; cad; repair; geometry cleanup

1. Introduction

Simulation of complex phenomenon in the earth sciences has been of interest to the mining sector since the advent of affordable computers. State-of-the-art modeling capabilities in mining encompass continuum and discontinuum approaches [1,2,3]. Hexahedral elements are desired over simpler element shapes when solving finite element or finite difference equations. Given the complexity of mine workings intersecting non-trivial geometry of the geology and structures, it is often difficult or impossible to produce an all-hexahedral grid for computations while honoring features deemed important to the physics of the problem. Splitting every tetrahedron of an all-tet mesh into four hexahedra is sometimes done, but this produces poorly shaped and often unusable hexahedra. A compromise is often made and hex-dominant meshes are used, sacrificing some accuracy in the response.

* Corresponding author

E-mail address: edzik@itascacg.com
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This paper focuses on an approach to address some of the challenges faced in constructing hex-dominant volume meshes for numerical modeling of mining applications. Section 2 provides a brief background on some of the meshing challenges faced in mining. Section 3 presents a custom solution, with a well-defined workflow that was developed to solve the meshing issues encountered. Section 4 presents other challenges and conclusions.

2. Background

Conformal meshes are often required for numerical modeling of mine stability problems. For generating conformal meshes, Owen et al. [4] describe the problem succinctly: "Robust geometric representations of the physical domain are generally required in order for mesh generation algorithms to be reliable." As [4] also points out, there are two broad schools of thought for representing geometry: 1) BReps (boundary representation) with NURBS (non-uniform rational basis spline) representations; and 2) facet-based models. NURBS can be difficult or impossible to fit to geological data, especially where the geometry is discontinuous and cross cut by other features. Figs. 1 and 2 highlight some of the mining and geological geometry complexities encountered. The left side of Fig. 1 shows a cross-section through hypothetical geology and geologic structures without any mine workings represented. The right side of Fig. 1 shows mine workings near a faulted area. Scale differences and model sizes are frequently unavoidably large. The undulating, kinked fault shown in Fig. 1 (right), was provided as a faceted model; this would be difficult to represent with NURBS. Fig. 2 shows as-built geometry provided by a mine. This faceted geometry contains mismatched, intersecting, duplicate, facets in addition to spurious features which require cleaning prior to any attempt at meshing. These geometries are extremely challenging to clean and mesh but their inclusion is necessary to understand the physics of the problems underground.

Advanced capabilities are commercially available for creating geometrically robust geological models from geological data (e.g., geology, ore-grade, structural features). These include implicit methods (e.g., radial basis functions, dual kriging) for automatically creating surfaces, of typically free-form shapes, directly from geological data. However, exports from implicit modelers typically consist of facetted surfaces. Because of this disconnection, between ore grade, mine planning software, and mesh generation numerical modeling software, an underlying geometric model is often not available to be used as a reference model for facet-based model clean-up such as that proposed by [5]. Implicit surface geological models may or may not include capabilities for including mine geometry in a manner that allows it to be conformally meshed with the geology.

Mine geometry is frequently provided as a reference surface mesh as shown in Fig. 2 which is not immediately suitable for re-meshing but is useful to the mine for surveying purposes, calculating ore grade, tonnage, and dilution. Some geological modeling tools produce good geometric models of geology (with smooth, free-form surfaces representing an ore-body for example), but might use similar "smoothing" techniques when creating meshes for mine-workings. Even though these surface meshes might be conformal, work is usually required afterward to modify the surface mesh so that it suitably represents the geometry for numerical modeling. In addition to cleaning up poor intersections, the surface meshes usually need to be re-meshed to a prescribed element size to suitably resolve areas of interest in the numerical model. This process can introduce new problem areas in the surface meshes.

Several common problems faced in mesh generation in the mining industry have been presented. Even for some seemingly straightforward topology, some meshing solutions, commercial and open source, fall short of providing a suitable mesh when dealing with mining-types of geometries. The following section describes an approach that was adopted to move past some of these obstacles.

3. Custom Solution

Given the stated problems, it was found that to devise a highly-automated approach was not the most efficient way to address the mining meshing problems. Geometry and mesh clean-up, surface remeshing, and volume meshing required a flexible interactive environment allowing a user to handle specific problems piecemeal. A commercial CAD system, Rhino [6], offered this through its OpenNURBS [7] initiative that provides CAD, CAM, CAE, and computer graphics software developers (C++ and .NET) the tools to accurately transfer 3D geometry between applications. The OpenNURBS initiative addresses some of the same shortcomings of early geometry engines as does the Common Geometry Module (CGM) [8] and was developed at approximately the same time. The OpenNURBS libraries are open, with source code freely available. The Rhino CAD system also provides users with the ability to write plug-ins (C++, C#, Python bindings) that can directly access most of Rhino's interactive functionality, the underlying geometry, and advanced geometric functions while running seamlessly with Rhino. In addition to handling non-manifold BRep models (Boolean operations, imprinting, trimming, etc.), Rhino also provides many surface meshing capabilities (e.g., meshing of non-manifold BReps, trimming meshes, editing facets, matching surface mesh edges, auto filling of holes).

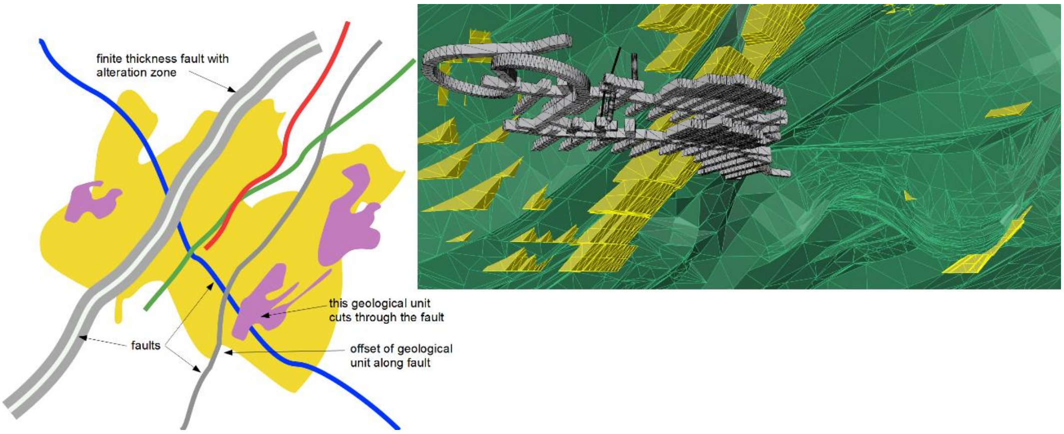

Fig. 1. Hypothetical cross-section of geology and structures (left) and actual mine and geological structure geometry (right). In the left view, the yellow and purple areas represent areas of different ore that are cross cut by faults, some with finite thickness. Faults are not always continuous, as shown by the red fault that terminates in the yellow ore body.

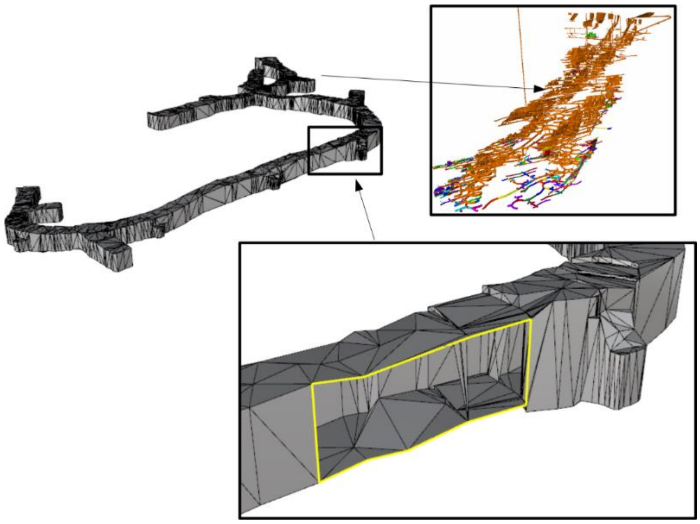

Fig 2. As-built tunnel geometry provided by a mine. Detailed view (lower right) showing portion of a tunnel surface mesh. Yellow boundary outlines area that has been opened intentionally to allow viewing of the interior of the tunnel mesh. Note the extraneous facets on the inside.

Rhino surface meshes are typically not suitable for numerical computation, but good for prototyping and machining. Rhino does not have built-in volume meshing capabilities. A meshing requirement was to have control over the discretization in specific areas of a model. One possibility to respect this need was to generate volume meshes from surface meshes and honor the surface facets in the volume mesh. Another requirement of the volume mesher was the ability to handle discontinuous features such as the faults shown in Fig. 1. Some commercial volume meshers require discontinuous features to be extended to completely intersect closed volume boundaries, which would be difficult given the complexity of the mine models.

It was decided to use Rhino as an interactive, graphical meshing platform. Surface mesh clean-up and remeshing, as well as volume meshing from facetted surfaces, would be handled by a set of commercial meshing libraries [9]. Rhino plug-ins were written by the first author to address the meshing requirements. These plug-ins interactively linked Rhino surface meshes to the commercial surface mesh clean up, surface remeshing, and volume meshing tools. The collection of plug-ins is called Griddle [10].

Griddle allows remeshing of facetted surfaces to triangle, quad-dominant, or all-quad surfaces. Remeshing can be done globally or locally with specified edge size constraints. Size fields and edge constraints can be specified through the Rhino user interface. Facetted meshes can be intersected to produce conformal meshes. Once satisfied with surface meshes, the Griddle volume mesher can fill the interior of the domain with volume elements, with volume element faces conforming to input surface mesh faces. Griddle operates directly on Rhino mesh data and transfers these surface mesh descriptions to the remeshing engines which return either surface or volume meshes. Surface meshes are translated back to the Rhino format for users to view and edit. Volume meshes are exported to external files for importing into numerical modeling software.

With the CAD meshing plug-ins, a simple workflow is followed (Fig. 3). Surface meshes that are used in step 1 can originate from a variety of sources, including BReps, point clouds, and contours. The meshes in step 1 aren't necessarily properly intersected and at the desired resolution. This is addressed with custom plug-ins for surface mesh intersecting and surface remeshing in steps 2 and 3. A user may be required to repeat steps 2 and 3 on portions of the model where global remeshing parameters did not necessarily produce acceptable meshes at all model scales. Once a conformal mesh of appropriate density and type is obtained, step 4, volume meshing, is a mere button press.

A portion of a model can be remeshed independently of other areas whether they are physically connected or not. Remeshing of a local area that is physically connected to another mesh region can be accomplished with the aid of edge constraints specified to maintain conformal connections between connected areas.

A plug-in was also written to disambiguate the selection of joined portions of non-manifold surface meshes. This resulted in huge time savings for users who dealt with dozens of complex intersecting surfaces which must be untangled prior to meshing and modeling. A user will typically identify important features (geology, faults, mine workings) of their surface mesh for remeshing using a specified size field, applying boundary conditions, establishing a mining sequence, or assigning material properties in the numerical model. These features are usually given names or placed in distinct layers in the CAD model. It was important to end-users to have their original mesh data (e.g., names, layers) remain intact after remeshing and this is a feature of Griddle.

Fig.4 shows a surface mesh that was obtained from scanned mine data and mostly "automatically" cleaned up using the described tools. Prior to the state shown in Fig. 4, raw surface meshes of mine and faults were read into Rhino, then intersected and remeshed as quad dominant meshes using Griddle. Surface meshes automatically kept their CAD properties during remeshing for ease of identification during modeling. Small problem areas that remained after remeshing, highlighted in Fig. 4, were easily cleaned up using Rhino's surface mesh editing functions.

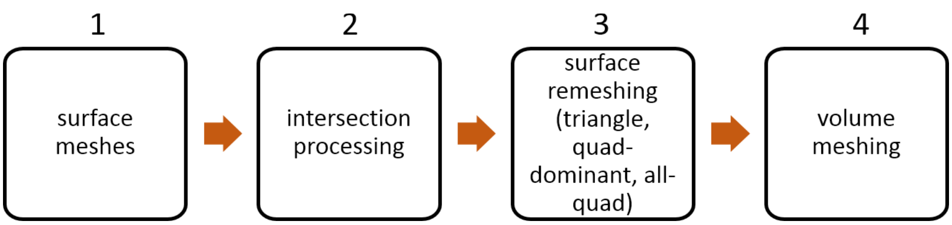

Fig. 3. Workflow with custom CAD meshing plug-ins.

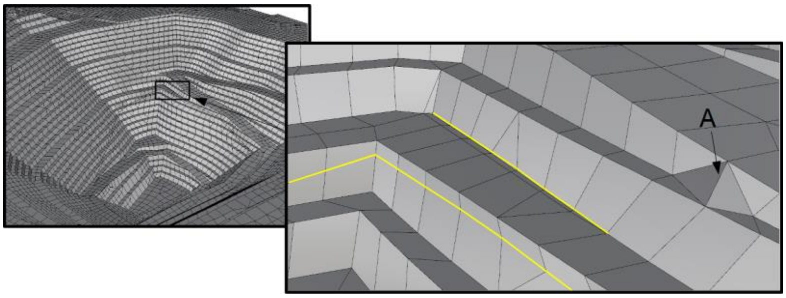

Fig. 4. Open pit mine meshed with Griddle. Edge A required manual swapping to correct ramp geometry. Yellow lines indicate trace of a fault that intersects the geometry. Upper yellow edges were manually collapsed onto adjacent ramp edges to eliminate sliver elements in the volume mesh.

4. Conclusions

The presented meshing solution has been used successfully on numerous mining problems over the past year. In addition to the powerful features of the meshing libraries, users attribute the success of this meshing approach to:

- the interactive, graphical nature of the CAD environment;
- local and global control over mesh size and type during remeshing;
- input surface mesh faces replicated by underlying volume mesh (what you see is what you get);
- custom handling of non-manifold surface mesh selections;
- piecemeal processing of meshes (allowing users to operate on portions of the mesh if desired);
- automated surface mesh patch recovery after remeshing (names and layers of remeshed patches preserved); and
- simple workflow.

Although the presented approach has made the creation of numerical model meshes for mining applications much more robust and simplified, there are still many outstanding issues. Merging narrow angle features requires more attention. Giving selected features a merging precedence, e.g., a minor fault might become part of a major fault when the two approach each other with a very small separation distance, might solve this problem. Clean up of automatically created meshes (e.g., from 3D laser scans) still requires a considerable amount of time to remove spurious spikes, folded areas, holes, overlapping coplanar areas, etc. Unfortunately, many of the clean-up and merging operations require human judgement, which requires knowledge of the geological history, interpretation of well logs, and knowledge of the mine geometry.

Mesh generation still forms a large portion of the total time of many mining projects requiring numerical modeling, but this time is being reduced with better and more reliable tools.

References

[1] P. Cundall, C. Detournay, Dynamic Relaxation Applied to Continuum and Discontinuum Numerical Models in Geomechanics. In: Rock Mechanics and Engineering, CRC Press/Balkema (in press).

[2] M. Board, R. Brummer, S. Seldon, Use of Numerical Modeling for Mine Design and Evaluation. In: Underground Mining Methods: Engineering Fundamentals and International Case Studies, pp. 483-491, W. A. Hustrulid and R. L. Bullock, Eds. Littleton, Colorado: SME (2001)

[3] J. Lemos, Recent developments and future trends in distinct element methods –UDEC/3DEC and PFC codes. In: Advances in Discontinuous Numerical Methods and Applications in Geomechanics and Geoengineering, pp. 17-29 (2012)

[4] S. J. Owen, D. R. White, T. J. Tautges, Facet-Based Surfaces For 3D Mesh Generation. In: Proceedings of the 11th International Meshing Roundtable, pp. 297-312 (2002).

[5] B.M. Smith, T.J. Tautges, P.P.H. Wilson, Sealing faceted surfaces to achieve watertight CAD models. In: Proceedings of the 19th International Meshing Roundtable, pp. 177-194 (2010).

[6] Robert McNeel & Associates: Rhino 5, Seattle, Washington, USA, www.mcneel.com

[7] http://developer.rhino3d.com/guides/opennurbs/what-is-opennurbs/

[8] T. J. Tautges, The Common Geometry Module (CGM): A Generic, Extensible Geometry Interface, Engineering with Computers, 17:3, 299-314 (2001)

[9] Computing Objects, 25 rue du Maréchal Foch, F-78000 Versailles, France, www.computing-objects.com

[10] Itasca Consulting Group, Inc.: Advanced Grid Generation for Engineers (Griddle^{TM}, Ver. 1.0, and BlockRanger^{TM}, Ver. 1.2, User's Guide). Minneapolis: Itasca. (2016).