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A systematic approach to unstructured mesh generation for ocean modelling using GMT and Terreno ☆

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ABSTRACT

A systematic approach to unstructured mesh generation for ocean modelling is presented. The method optimises unstructured meshes to approximate bathymetry to a user specified accuracy which may be defined as a function of longitude, latitude and bathymetry. GMT (Generic Mapping Tools) is used to perform the initial griding of the bathymetric data. Subsequently, the *Terreno* meshing package combines automated shoreline approximation, mesh gradation and optimisation methods to generate high-quality bathymetric meshes. The operation of *Terreno* is based upon clearly defined error measures and this facilitates the automation of unstructured mesh generation while minimising user intervention and the subjectivity that this can introduce.

1. Introduction

In this article a method for producing unstructured meshes to optimally represent complex oceanographic domains is presented. The primary goal is an initial mesh which will be used in oceanographic simulations using numerical circulation models with dynamically adaptive mesh capabilities. Additionally, the meshes produced should also be of sufficient stand-alone quality to be used for non-adapting unstructured mesh simulations.

Fundamental to 3D operational ocean modelling is the suitable approximation of bathymetry and shoreline. The poor representation of bathymetry can lead to problems in modelling, for example, boundary currents (Özgökmen et al., 1997; Stern, 1998; Tansley and Marshall, 2000) which can have a serious impact in the quality of the entire simulation. The inadequate representation of the shoreline may also lead to problems such as the imposition of spurious stresses (Adcroft and Marshall, 1998). In both cases, small edge lengths in the mesh can place impractical constraints on the time stepping that can be used (e.g. the CFL condition, Durran, 1999). In oceanographic applications it is generally unknown to what extent the choice of an accurate domain boundary representation affects the overall quality of the simulation. In addition, there is a trade-off between how close the surface mesh approximation of the bathymetry conforms to reality and how appropriate it is for numerical modelling (e.g. number of mesh elements, mesh length scale and time stepping).

Compared to the classically used structured mesh in ocean modelling, unstructured meshes allow far greater freedom in the representation of complex geometries. In addition, they can be used with adaptive mesh techniques to dynamically alter the local mesh resolution and alignment to best fit the solution characteristics throughout the course of a simulation (Pain et al., 2005; Piggott et al., 2005). However, when mesh adaptivity methods are employed it is necessary to keep the shape of the domain fixed (i.e. topographical features should neither be added nor removed) to avoid violating volume or mass conservation principles (free-surface and flooding models

☆ Code available from server at https://sourceforge.net/projects/terreno and http://www.iamg.org/CGEditor/index.htm

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also change the domain but aim for conservation). This means disallowing any local adaptive mesh operations which change the topography, as would occur if the mesh nodes were continually being mapped to a parametric model of the domain for example. Such domain mapping is commonly used in CFD (computational fluid dynamics); however, conservation becomes more important as the integration time increases. Note, this restriction does not preclude the refinement of elements on the surface, nor subsequent reversal of these refinements to the original surface discretion as the domain shape is unaffected. Therefore, it is important to have as good ('good' being dependent on levels of detail required by the particular simulation in question) a discrete mesh approximation of the domain as possible from the beginning of the simulation using a minimum number of nodes or elements. The number of nodes and elements used to represent the domain boundary directly limits the minimum cost of a simulation. This provides the motivation for the mesh to be optimised everywhere with respect to this trade-off to yield a representation of the domain geometry to an accuracy sufficient for the user's requirements (perhaps based upon sensitivity studies) using the minimal number of degrees of freedom.

Many unstructured mesh generators, such as *TriGrid* (Henry and Walters, 1993) and *Triangle*,[1] are based on constrained Delaunay triangulation methods. These methods may be viewed as taking a top-down approach to bathymetry approximation using unstructured meshes, i.e. one begins with a coarse mesh and adds vertices until the required vertex density has been obtained (see Legrand et al., 2000 for a Delaunay approach on the sphere which allows higher vertex densities in regions of interest). Conversely, the approach taken here is a bottom-up approach whereby one starts with a mesh containing all available data (from multiple sources and of varying resolutions perhaps) and the mesh is coarsened using mesh optimisation to obtain the desired level of approximation. In general, bottom-up approaches are more expensive to compute than top-down approaches. However, bottom-up approaches permit a more thorough error analysis of the data to be performed and so can generate more accurate approximations with the same budget of facets. *Triangulated irregular networks* have been employed for real time rendering and visualization of large terrain data sets (Garland and Heckbert, 1995; Hoppe, 1996; Lindstrom et al., 1997; Duchaineau et al., 1997). The focus in these applications tends to be on reducing the size of the data set quickly and the result must be suitable for visualisation of a height field to a given level-of-detail. However, for ocean modelling the focus is on efficient height (i.e. here bathymetry) field approximation with a formal error estimate. This allows the approximation error to be controlled according to the demands of the ocean model, and for some statements to be made about the errors in the ocean model itself. In addition, for an ocean model there is just a one off cost associated with generating a bathymetric approximation. Therefore, efficiency of approximation takes precedence over the cost of computing the approximation.

Terreno[2] uses a 2D anisotropic mesh optimisation algorithm to explicitly optimise for element quality and bathymetric approximation while minimising the number of mesh elements created (Gorman et al., 2006). The shoreline used in the mesh generation process is the result of a polyline approximation algorithm. In this case the minimum length of the resulting edges is considered as well as the distance an edge is from a vertex on the original shoreline segment being approximated (Gorman et al., 2007). The underlying philosophy is that meshing and approximation should be error driven and should minimise user intervention. The latter point is doubly advantageous: usability is paramount and the user need not be an expert in mesh generation to produce high-quality meshes for an ocean model; additionally there must also be clearly defined objectives to the mesh generation process to ensure reproducibility of results. The result is an unstructured mesh, which may be anisotropic and focuses resolution where it is required to optimally approximate the bathymetry of the domain. The criterion to judge the quality of the mesh is defined in terms of clearly defined objectives. An important feature of the approach is that it facilitates multi-objective mesh optimisation. This allows the user to simultaneously optimise the approximation to other variables in addition to the bathymetry on the same mesh, such as back-scatter data from soundings, material properties or climatology data for example.

The remainder of this article is laid out as follows. The next section describes the initial bathymetric and shoreline data required for mesh generation in ocean modelling. *GMT*[3] is used to pre-process source data, in a number of different scenarios, to create a suitable input data set for Terreno. Section 3 describes the error measures used to control the shoreline and bathymetric approximations. Section 4 details the mesh generation pipeline used and shows the result of the method when applied to the Irish Sea. The final section gives some concluding remarks.

2. Data preparation

Terreno takes as input bathymetry, shoreline data and a set of options to control the mesh generation process. Bathymetry should be either in the form of an initial unstructured triangular mesh, possibly generated by blending together data sets of differing resolution, or a gridded data set. For the purposes of bathymetric approximation and optimisation, the bathymetry is treated as a scalar field stored node-wise on a flat 2D mesh. Since the surface mesh is initially projected to a flat plane, the only geometrical constraints on the mesh are those imposed by the 2D domain boundary (i.e. the shoreline).

[1] Triangle: http://www-2.cs.cmu.edu/~quake/triangle.html

[2] *Terreno*, released under the GNU General Public License, is available from https://sourceforge.net/projects/terreno

[3] *GMT* (*Generic Mapping Tools*), released under the GNU General Public License, is available from http://gmt.soest.hawaii.edu/