Image Based Meshing; OpenFOAM export for ScanIP

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ABSTRACT

One of the most time-consuming elements of CFD analysis is the meshing process. Creating a good mesh requires significant input of human time and expertise, yet can be critical in generating accurate results. Image Based Meshing (IBM) is a process whereby 3d scans of a patient can be used to generate both the geometry and mesh for solution. Simpleware Ltd has developed and markets software (ScanIP) to process these image stacks and we have now developed an export stage to allow the native export of OpenFOAM format meshes, to complement formats for other FEA and FVM codes. These techniques provide a powerful and elegant meshing tool for CFD; initially used for biomedical problems, but which can be applied for any problem where the geometry is complex or unknown but an object exists which can be scanned. The use of the software will be demonstrated with reference to example cases in biomechanics (blood flow in the Circle of Willis) and other areas of engineering (flow in packed beds, engine intake manifolds).

1 Introduction

The meshing process is one of the most critical and time-consuming elements of CFD analysis. Costly in human time, the quality of mesh can be a significant factor in determining the accuracy or even the success of the simulation. This is particularly important in the case of biomedical flow problems, such as blood flow in arteries and human respiratory flow, where in addition to the meshing problems, even defining the geometry is a significant problem. Geometries for biomedical flow problems are very complex; an artery is a pipe, but one with a cross sectional shape and size and orientation which are continuously changing along its length. Defining such a shape in CAD would be very difficult, requiring numerous measurement, and would be very time consuming. Moreover everyone's arteries are geometrically different, so the process would need to be repeated for each new patient. Image Based Meshing (IBM) is a process whereby 3d scans of a patient can be used to generate both the geometry and mesh for solution. Scans, typically from MRI or CT scanning, comprise stacks of 2d images representing cross-sections of the patient at regular intervals. These therefore represent 3d geometric information which can in theory be processed automatically to generate domain geometries and meshes. The objective is to make this process as highly automated as possible, with the aims of making it efficient and quick but also of eliminating human factors in the process.

Two basic approaches are used in the literature and in existing IBM codes. The first approach we term CAD-based; automated edge-detecting algorithms can be used to identify bounding surfaces of the structures in the images, which can then be exported in CAD format (usually as a triangulated surface, eg. STL format) for import into a pre-existing automatic mesh generator. This is a relatively simple process, although edge detection is itself a complex task, but is unsuited to very complex cases. The alternative is voxel-based. A stack of (pixel-based) images represents a structured block of rectangular 3d pixels or *v*oxels, each of which can be regarded as having a value associated with it which relates to the physical properties of the object in that region of space. Voxels with similar values representing the region of interest (ROI) can be agglomerated into a mask from which the 3d mesh can be generated directly [8]. This approach is used in the code ScanIP developed and marketed by Simpleware Ltd [1].

2 ScanIP

ScanIP is the core code developed by Simpleware Ltd for voxel-based IBM processing, covering image stack import and multipart segmentation. Tools are available for detailed processing, both to work on the images (individually and throughout the stack) and to create and manipulate the segmented masks. Image processing operations include various smoothing and sharpening filters, noise reduction etc. Segmentation can be carried out in a number of automated ways, including by thresholding, floodfill (a region-growing algorithm based on threshold values), and also manually, allowing painting of regions by hand (used where necessary to tidy up the segmentation). The mask is then truncated at the surface and smoothing applied to create an STL representation of the structure for export.

Associated with the core ScanIP code are two additional modules; +CAD and +FE. +CAD allows the introduction and manipulation of additional geometric elements in the form of CAD files into the image stack; this provides the capability to model say artificial hip replacement by introducing these elements into the stack. The other package is +FE, which provides the capability to generate and export FVM and FE meshes in a number of commonly used formats for CFD and CSA use. ScanIP+FE is capable of generating both tetrathedral, hexahedral and mixed (tet/hex) meshes using two different mesh generation algorithms. The first, +FE-Grid, uses the marching cubes algorithm to generate a base cartesian mesh which is then truncated and smoothed at the ROI boundaries as defined by the mask, in a similar manner to OpenFOAM's `snappyHexMesh`. This is a fast and robust meshing algorithm which can deal with topologically highly complex cases [2]. A second meshing algorithm is also available, +FE-Free, which uses the surface triangulation generated earlier and Delaunay triangulation [???] to generate a volumetric mesh. This permits greater control over the meshing (such as automated feature-based mesh refinement) and provides for a smaller cell count. Adaptive decimation, smoothing, and boundary layer generation are all possible, as is user-defined mesh density control. Also, arbitrary numbers of masks can be generated and converted to separate computational meshes, which are guaranteed to be conforming at the interfaces; i.e. the corresponding surface meshes where two separate regions meet possess the same geometric and topological structure.

CFD export has long been possible in the form of Fluent-format .msh files [3, 5]. Recently, Simpleware in collaboration with researchers at the University of Exeter has worked to develop a native OpenFOAM format export module. This will export the `polyMesh` directory files for OpenFOAM analysis.

3 Examples of OpenFOAM use

Here we present two case studies of the use of ScanIP+FE to generate OpenFOAM meshes for analysis. The first is a biomedical case, a study of blood flow in the Circle of Willis. This is funded by a grant from the Royal Devon and Exeter Healthcare Trust, and is part of a project to investigate the effect of patient-specific variation of the vessels in the brain. Several healthy individuals have been scanned, as have a number of stroke patients, and work is under way to look at the use of CFD in analysing blood flow in this structure in the brain. The second case is the reverse-engineering of a car inlet manifold from an MRI scan, which was undertaken to demonstrate the range of possible uses of IBM techniques.

3.1 Flow in the Circle of Willis

The human brain is supplied by blood from three arteries, the left and right carotid arteries and the basilar artery at the back of the neck. These are joined by interconnecting arteries within the brain forming a structure known as the Circle of Willis, from which further efferent arteries supply the main regions of the brain with blood. This structure is therefore of key importance in supplying blood to the brain, and unusually within the circulatory system is capable of a fair degree of resiliance; the blood flow through the interconnecting arteries can go in either direction, and blockage of one or more of the afferent arteries can be compensated for. Understanding the blood flow in this structure is therefore of significant interest in the study of strokes; their occurrence, surgical relief and rehabilitation. Moreover the structure itself exhibits a range of geometric features, in particular being incomplete or otherwise malformed – in fact only about 40% of subjects possess a 'normal' Circle of Willis.

Data from a healthy 50-yr old volunteer has been processed for this study. MRI (Magnetic Resonance Imaging) was carried out to generate the image stack which was then imported into ScanIP+FE for mesh generation. Figure 1 demonstrates the sequence of operations, starting with the basic scan data (illustrated by 1.a.), segmentation by thresholding, floodfill to generate a completed mask and geometry (1.c). This was then meshed using the +FE-Grid mesher and exported as an OpenFOAM `polyMesh` file set. (The +FE-Free mesher was also used; the results shown here are from the +FE-Grid case however).

Computation of the flow also requires the knowledge of the boundary conditions. Outlet conditions were set to a constant outlet pressure which is physiologically defensable. The inlet flow will be pulsatile in nature, and the shape of the pulse will depend on the details of the patient's exact cardiac cycle. Two approaches have been tested so far. In the first, `groovyBC` was used to apply a simple sinusoidal inlet velocity with an appropriate peak systolic flow. As an alternative, a typical cardiac cycle waveform was split into segments and the `mapped` boundary condition used to generate a time-dependent inlet condition. Both have been shown to work quite adequately, and we have plans to measure the inlet conditions as part of future scans.

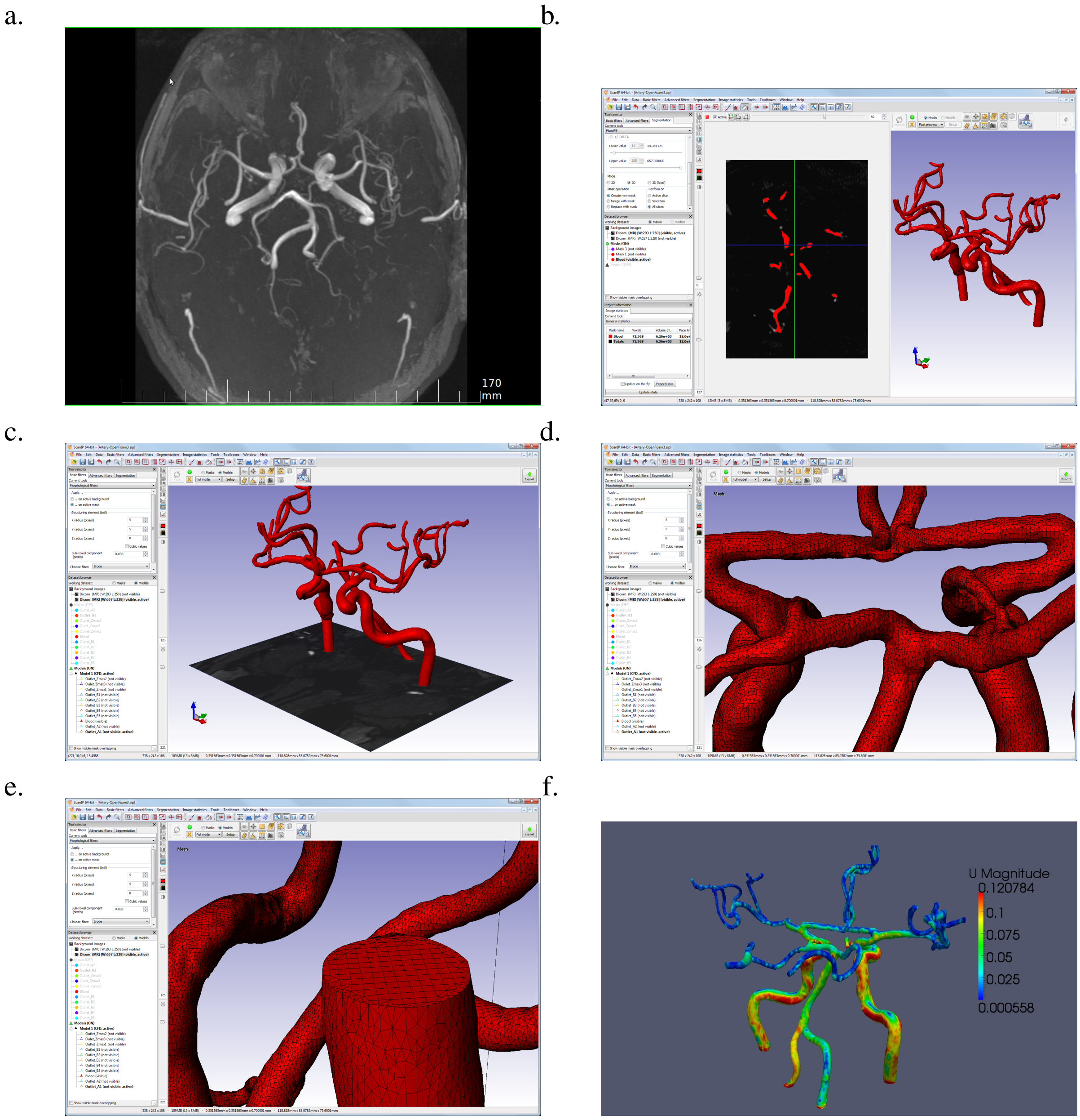

Figure 1: Segmentation of Circle of Willis data; a. original DICOM data, b.thresholded and floodfilled segmented mask, c. resulting geometry. d. meshed geometry, e. closeup of mesh. f. typical CFD results.

3.2 Engine intake manifold

IBM, and specifically ScanIP+FE, does not have to be confined to biomedical applications, but can be applied to any problem where the geometry to be analysed is complex (and possibly unknown) but a physical object exists that can be scanned. Examples include applications in botany [4], chemical engineering [2], microstructural flow [7] and others [6]. As an example, we demonstrate the proceedure by reverse engineering the geometry for an engine intake manifold. The manifold (figure 2.a.) was CT-scanned and ScanIP+FE used to generate the geometry and mesh (figures 2.b.c). The resulting mesh was high quality and a simple CFD calculation performed in order to demonstrate the output (figure 2.d.).

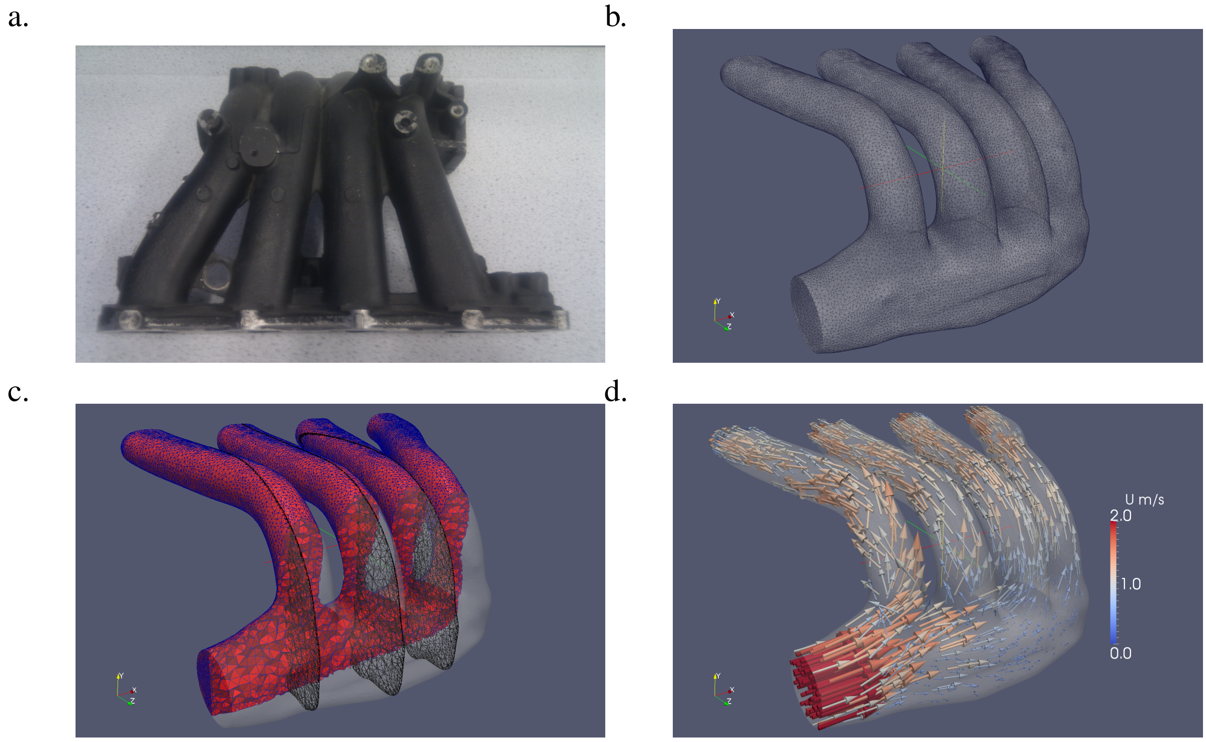

Figure 2: Analysis of engine manifold; a. physical manifold, b.surface mesh, c. internal mesh. d. typical CFD results.

4 Conclusions

Image Based Meshing demonstrates great potential for developing meshes for any problem where a physical object is available to be scanned. Originally a medical based technique, it can be used to construct meshes for numerous complex flow problems; examples are given for its use in examining flow in the Circle of Willis and for reverse-engineering an engine manifold. The work done here demonstrates the potential of IBM and the ease of use of the tools combined with OpenFOAM.

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