OPEN CASCADE AND RAPID PROTOTYPING IN HUMAN CAROTID LUMEN RECONSTRUCTION

Fabrizio Murgia
CRS4[*] - EIP[†] - GEMMS[‡] VI Strada OVEST Z.I. Macchiareddu, C.P. 94, 09010 UTA (CA - Italy)
ph +39 0702796321, fax +39 0702796216, e-mail: fmurgia@crs4.it
Gabriella Pusceddu
CRS4 - EIP - GEMMS VI Strada OVEST Z.I. Macchiareddu, C.P. 94, 09010 UTA (CA - Italy)
ph +39 0702796321, fax +39 0702796216, e-mail: gabri@crs4.it
Gregorio Franzoni
CRS4 - EIP - GEMMS VI Strada OVEST Z.I. Macchiareddu, C.P. 94, 09010 UTA (CA - Italy)
ph +39 0702796347, fax +39 0702796216, e-mail: franz@crs4.it

Abstract:

Image processing algorithms, CAD-CAM tools and rapid prototyping (RP) techniques are able to produce complex lumen artery replicas. This work presents a system for manufacturing the lumen of human carotid from computed tomography acquisition. The pipe-line of manufacturing process of a human carotid lumen replication is presented. Each stage of the pipe-line is briefly discussed. Technical details of the 3D surface reconstruction phase, based on the Open Cascade geometric modelling software, and the RP manufaturing process based on Fused Deposition Modelling are presented.

Keywords: Rapid Prototyping, Geometric Modelling, Medical Imaging

1 Introduction

Rapid Prototyping (RP) is an emerging technique used in industry for manufacturing prototypes [11]. RP can be considered a new imaging technique. Its capability to physically reproduce geometrical complex shapes is getting increasing interest in medicine [5]. Stereolithographic biomodelling has already been used in craniofacial surgery for management of deformities, traumas and tumours. Accurate analysis of Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) data of a patient is a common practice in vascular surgery. Surgeons try to mentally reconstruct a virtual 3D surgical anatomy model. Physical models can help in this important task providing the physician with a visual and tactile support [8], [4]. Physical replicas can also facilitate experimental studies of computational vascular fluid dynamics [3]; they also permit in vitro reproductions of flows in living subjects before and after surgery.

The CT data are transmitted from the acquisition clinical apparatus to the graphics workstation. The replica manufacturing process starts with making a segmentation step. It is necessary to extract the set of points (curves) which represents the lumen. This step is a semi-automatic

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[*] Center for Advanced Studies, Research and Development in Sardinia
[†] Energy and Process Engineering
[‡] Geometric Modelling and Monte Carlo Simulations

process aided by an image processing tool. These points are linked together, by using commercial CAD-CAM systems to build 3D surfaces. This step is called the geometric reconstruction. BSpline are used to define the geometry of curves and surfaces . The last stage of the pipeline is Rapid Prototyping. At this point the surfaces are tessellated to obtain the mesh of triangles in STL format which is the input format for the RP device; RP device builds the object using a layer-by-layer manufacturing process.

Pentecost group [10] used a digital photomicrograph (10 micrometers section thickness) apparatus to reconstruct the cardiac blood space of human embryonic heart (approximately the greatest dimension of the embryo is $3.5mm$). The curves representing the lumen were manually traced from the photos and reconstructed in surfaces by using Maya software (*http://www.aliaswavefront.-com/*). The replicas were built using a Stereo Lithographic Apparatus (SLA) with layers thickness of $0.0254mm$.

Lermusiaux work [7] reports the use of CT scan acquisition (the reconstruction interval of $2.5mm$ every $1.3mm$ and a pitch of 0.7) with contrast liquid and without cardiac synchronisation during the acquisition procedure. An unspecified semi-automatic image processing tool, driven by the operator, is used to generate a structured points cloud and to compute the interpolated surfaces from adjacent sections. The STL model is sliced in $0.1mm$ cross sections. SLA 250 (3D Systems Corp. Valencia, CA) is used to build the physical replicas in epoxy resin. The system was developed to reconstruct abdominal aortic aneurysm (AAA). Three days were required to produce the final replica.

Renaudin group [2] used MRI apparatus (a 3D MR angiograph $1.5T$ and static MR imaging echo setting with $1mm$ pixel size dimension) to develop a complete phantom of the coronary arteries dedicated to 2D or 3D angiographic imaging. The system can also be used to construct a realistic phantom of stenoses of the coronary arteries. The CAD Euclid system (from Matra-Renault *http://www.matra-datavision.com/)* was used to build 3-D anthropomorphic phantoms. The segmentation was done by using parametric curves (B-Spline) starting from center lines of the vessels manually computed by an expert operator. Phantoms were built using a SLA technique (manufacturing precision is under $0.1mm$ that can be improved till $0.01mm$). The phantom can also be used for testing 3D reconstruction of vessels.

Friedman [1] used a slightly different approach to manufacturing vascular replicas that can be used for testing in vitro reproduction of flows in living subjects: a MRI acquisition apparatus (1.5 T GE). 3D time-of-flight imaging sequence is used to produce sixty sections $1.5mm$ thick with a pixel size of $0.8 \times 1.6mm$. Points were Fourier interpolated to $0.8 \times 0.8mm$ has been used. He used an ad-hoc image processing routine manually driven by the operator to define 120 points for each lumen curves. These points were equally spaced around the perimeter of each axial section. A CAD system was used to interpolate these points in BSpline surfaces. These surfaces were transferred (by using IGES format) to the powerful commercial CAD-CAM system Catia (*http://www.catia.com*). Both, two mold parting planes and the tool path for numerical controlled process were created in CATIA. A replica of real artery was milled out by a machinable plastic device. The distance between each final step of the cutter was $0.012mm$ producing scallops $0.008mm$ high. The run time was 3.5 h.

Our study follows a previous work made at CRS4 on the development of the ViVa system [3]. In this work we have investigated the applicability of RP technique in the vascular surgery field. We focused on applying RP technique to the carotid lumen reconstruction of a human artery acquired through Computed Tomography (CT).

2 Materials and methods

2.1 Data acquisition

Digital data were obtained by spiral CT on a patient affected by carotid aneurysm. The examination was performed using a Picker scanner at the Brotzu Hospital in Cagliari. Data was transferred to our workstation by using DICOM3 (*http://medical.nema.org*) standard protocol. We considered 48 CT images for this case. The distance between slides (derived from CT acquisition) is $1mm$.

2.2 Segmentation

The picture segmentation is a semi-automatic process driven by the end user (operator).
In this stage each CT image is filtered to extract points belonging to the lumen boundary.
Figure 1 shows a typical CT image after filtering. The lumen to be reconstructed is the boundary layer which separates dark pixels (inside lumen) from grey pixels (intima).

For the segmentation we used gsnake (*http://www.cs.wisc.edu/computer-vision/projects/gsnake.html*) library. The segmentation process starts opening a CT image, selecting the region of interest (ROI) on the image and positioning a contour of 3-D points inside the lumen region. At this point, an iteration loop starts moving points to lumen regions.
When all points reach the lumen boundary the evolving process stops and the cartesian coordinates of each point is stored in an indexed vector of 3D vertices. This stage is costantly monitored by the operator that fixes the number of iterations and some other parameters. This vector represents the geometric constraints for requested interpolation curve. This segmentation procedure is repeated semi-automatically for each CT image. This procedure generates 24 slides, each one storing 128 3D vertices (Fig. 1).

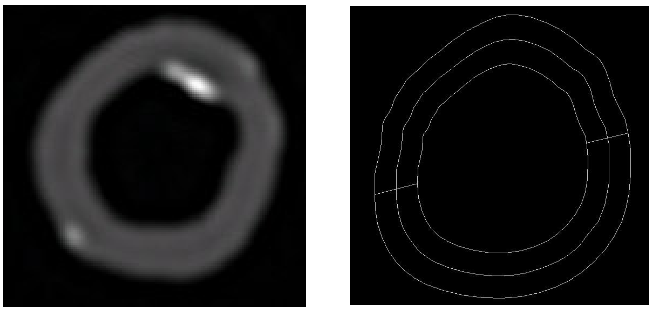

Figure 1: *Acquisition and segmentation steps. The left image shows the filtered CT image of a carotid (2.1). The right image shows the results obtained applying the segmentation step and interpolating the points by a BSpline curve (see 2.2).*

2.3 Geometric reconstruction

The lumen reconstruction is realised using the Open CASCADE (OC) (*http://www.opencascade.com*) software. OC is a powerful 3D modelling application development platform. It consists in reusable C++ object libraries and development tools that are available as Open Source.

OC is used to create domain specific 3D graphic applications such as: Computer Aided Engineering (CAE), Architecture Engineering Construction (AEC) and Geographic Information System (GIS), CAD-CAM.

We use the OC's Boundary Representation (BRep) scheme [6] to manage the model reconstruction of the lumen and to convert it in STL format. In fact, the topological library supported by this program allows us to build the valid topological data structure of the artery.

The set of parameterized points produced by the segmentation and stored in a file, are divided in horizontal planes. These points are stored into an array of *gp_Pnt* (OC data structure). We interpolate points belonging to the same plane by a BSpline curve using the *Geom_Api_Interpolate* class of OC. We use Bspline because such a representation presents a local control feature. This means that modifying one control point (vertex) only affects the part of the curve near that control point (Figure 1). In order to obtain a valid Brep object of the OC class *TopoDS_Solid*, we compute the previous interpolation algorithm for each slide by *BRep_Builder_API_MakeShell* and *BRep_Builder_API_MakeSolid* classes.

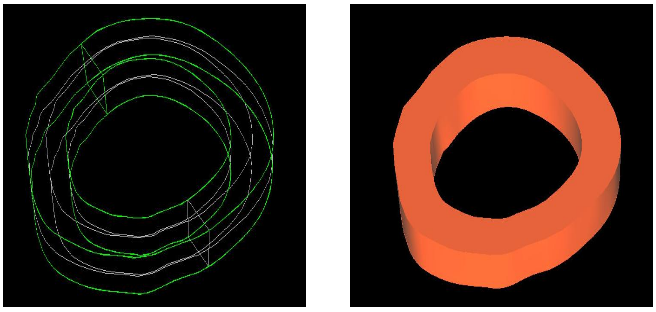

Figure 2: *Reconstruction step. The image on the left shows two Bspline curves obtained in the geometric reconstruction and segmentation steps (2.3).*

The left image in Figure 2 shows the Bspline surfaces obtained interpolating two adjacent Bspline curves. The inner surface represents the requested artery lumen. This surface has continuity C2. The outer surface represents an offset surface necessary to give the right manufacturing thickness to the physical replica. The inner and the outer surfaces are capped on the top (right image) and on the bottom by holed plane dishes in order to compute a valid BRep scheme with OpenCascade (2.3)
This solution is obtained overcoming both, numerical problems due to the BSpline curves/surface computation and problems due to topological aspects in the definition of the BRep (ex: orientation of computed surfaces). At this point, the solid model is completed and its BRep represents a valid 3D solid [6]. Last step is the tessellation of the BRep with triangles by *Stl_API_Writer* class of OC. This class produces the mesh of triangle that is stored in a output file using the STL format (Fig. 3)

The number of triangles produced by *Stl_API_Writer* class is kept low (setting tessellation parameters of OC) because the FDM apparatus defines an upper bound limit on the number of triangles. Because the STL file has been generated from a valid BRep representation no manual operation is needed from the RP operator to fix it. Surface model of the carotid lumen in each of the above specimens was converted to STL format in the previous step and transmitted to our prototyping center Proto21. Proto21 uses a RP machine with FDM technology. FDM means Fused Deposition Modelling, and is a technique whereby digital surface models are converted to scale models of resin or wax. It works by means of a moving head which is driven on the XY plane by the coordinates data in the 3D wireframe surface model. While moving, this head extrudes a fused wire of material which solidifies producing a thin layer (0.178 to 0.5 mm) of the object.

2.4 Rapid Prototyping

Then the workplane moves down along Z-axis of exactly the thickness of the layer created, and another layer is built up over the previous. The process goes on layer by layer, and creates a pretty accurate solid resin model. In our case, resin was ABS and the machine was a Stratasys FDM 2000 [9]. The manufacturing orientation is shown in Figure 3. This position has been chosen in order to have the maximum manufacturing resolution along the lumen axis. This mesh is obtained from Open CASCADE by the tessellation process and stored in STL format during the geometric reconstruction step (see 2.3).

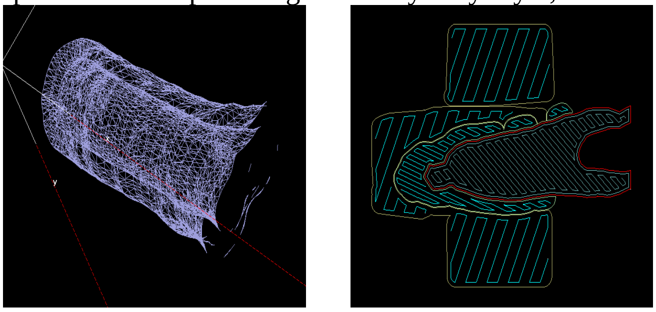

Figure 3: *Rapid Prototyping. The mesh of triangles positioned in the manufacturing Stratasys FDM 2000 position is shown on the left. The right image shows the machining path of the FDM disposal (SSL format) on a manufacturing cross section (see 2.4).*

3 Discussion and conclusions

Lumen replicas can help vascular surgeons in diagnosy and therapy of particular carotid diseases. In order to be able to plane the operation, vascular surgeons need to know, with great accuracy, the anatomy of the part. The physical model provides a visual and a tactile support that can improve the communication quality between surgeon and surgical equipe between surgeon and the patient. Replicas are also important for training scope. Lumen replicas of human carotid offers a mean to visualise internal anatomic features difficult to see otherwise.

The first production of the lumen replica is shown in Figure 4. The FDM technique is fairly cheap. Its cost is continuously decreasing and depends of the height of the artery to be manufactured. The building process for the lumen replica was rather fast, it took four hours to build a complete 3D lumen replica. For future models we are planning to use transparent materials (silicone) instead of ABS. We are also planning to include markings to distinguish pathological areas from healthy ones.

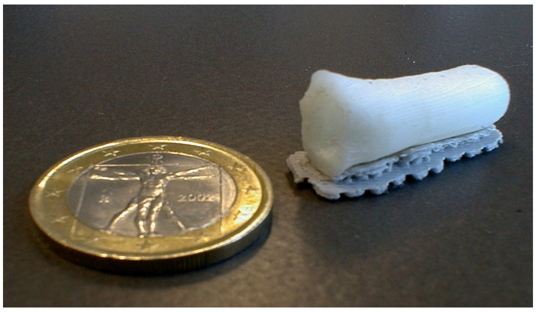

Figure 4: *This image show the physical reconstruction of the carotid in FDM. The printing stage is about 30 minutes.*

The system developed so far is a prototype. It is a part of undergoing research project: *Laboratory for Advanced Planning and Simulations* (*http://www.crs4.it/∼ laps/*).

Preliminary results presented herein demonstrate mainly how to use the Open Cascade library and FDM technique to build a lumen replica. It provides a software environment where we can verify different interpolation and blending surface algorithms supported by OC. We have also checked the capability of OC to generate correct tessellated geometries which can automatically be sent to the FDM device without any further intervention of the RP operator. Next phase of this study will be devoted to segment complex carotid CT data to automatically extract complex geometric and topological features (reconstruction of the carotid bifurcation). This technique, developed in collaboration with the

Radiology Dept. and the Vascular Surgery Dept. of the Ospedale Brotzu of Cagliari, will be used, in the next stage of the project, to reconstruct the carotid replicas of 10 patients with different carotid pathologies in order to study applicability of this technique to a minimum number of cases.

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