
Tagged Volume Rendering of the Heart: A Case Study

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Abstract

This is a companion paper describing the process and parameters for tagged volume rendering of the heart. We firstly review the relevant concepts and consider the problem of visualising the coronary arteries from computed tomography angiography (CTA) images. We then discuss the implementation using the SharpImage prototyping environment. Finally, we list the set of commands capable of reproducing our results using the accompanying dataset.

Keywords: *tagged volume rendering, heart, coronary arteries, ITK, SharpImage*

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1 Introduction

For diagnostic and treatment planning purposes, radiologists and surgeons require means to visualise the coronary arteries from computed tomography angiography (CTA) images. However, this task is non-trivial for various reasons: (a) unwanted structures (such as the thoracic cage) clutter the regions of interest; (b) the contrast agent highlights the coronary arteries (as desired), but also portions of the ventricles, atria, aorta, and pulmonary arteries, and (c) the coronary arteries can exhibit high-intensity calcification artefacts. Clinicians currently have a number of tools at their disposal, including: thin slab maximum intensity projection [1], curved planar reformatting [3], and direct volume rendering (DVR).

In the case of direct volume rendering, the dataset is segmented during the rendering process ('on-line') via a lookup table ('transfer function'). Various online segmentation algorithms for DVR have been discussed in the literature [8, 4, 12]. Kniss et al. [4] advocated the use of two dimensional transfer functions dependent on pixel value and gradient magnitude (termed 'value-magnitude' transfer functions), in which the user interactively specifies the function using a number of widgets. This method is simple, fast and effective for simple datasets; yet, it is insufficient for delineating objects of interest sharing similar characteristics. Tzeng et al. [12] proposed an approach using an online machine learning algorithm (such as an artificial neural network or support vector machine), with the current pixel value, gradient magnitude, location, and neighbourhood values as inputs. Because of their online nature, both of these methods are constrained by the graphics hardware on which they are implemented.

A number of more recent methods combine both offline and online segmentation. Hadwiger et al. [2] proposed tagged volume rendering which uses a number of *a priori* segmented binary masks ('tags'), each assigned separate transfer functions. Kniss et al. [5] introduced a probabilistic method which decouples classification from colour-mapping, simplifying the transfer function interface. Weber et al. [13] proposed the use of contour-trees for classifying objects based on topology (the trees are computed and simplified offline before being uploaded to the graphics hardware). Of these methods, tagged volume rendering is the most flexible as it does not restrict the choice of segmentation algorithm.

In this paper we apply tagged volume rendering to the problem of visualising the coronary arteries. We utilise Hessian-based line filters for segmenting the coronary arteries [9] and use the Fast Marching active contour method [10] for segmenting the pericardial cavity. A suitable speed function is presented for controlling the expansion of the active contour. The exact set of SharpImage [6] commands for reproducing the results on the accompanying dataset are given. For your reference, a pre-print of the main MICCAI paper can be found here: <http://eprints.qut.edu.au/archive/00008421/>

2 Implementation

This section details the implementation of the method. It requires built versions of ITK 3.2, ManagedITK 3.2.0.3 [7], and SharpImage 0.9.2 [6]. Before tackling the case study, we must extend the SharpImage environment to handle vessel segmentation and implement a fragment shader for tagged transfer functions.

2.1 Vessel Segmentation

SharpImage does not have an explicit vessel segmentation command, however it is quite easy to add such a script. The first step is to wrap the required filters using a ManagedITK external project (see `source/vesselness/CMakeLists.txt`):

```

1 PROJECT (WrapVesselness)
2
3 # Find required packages
4 FIND_PACKAGE (ITK REQUIRED)
5 FIND_PACKAGE (ManagedITK REQUIRED)
6
7 # Use required packages
8 INCLUDE (${ITK_USE_FILE})
9 INCLUDE (${MANAGED_ITK_USE_FILE})
10
11 # Wrap the project
12 BEGIN_MANAGED_WRAP_EXTERNAL_PROJECT ("Filtering" "Vesselness")
13   SET (MANAGED_WRAPPER_OUTPUT "${CMAKE_BINARY_DIR}")
14 END_MANAGED_WRAP_EXTERNAL_PROJECT ()

```

We need to wrap two filters, `itkHessianRecursiveGaussianImageFilter` and `itkHessian3DToVesselnessMeasureImageFilter`:

```

1 # Begin the wrapping
2 WRAP_CLASS ("itk::HessianRecursiveGaussianImageFilter")
3
4 # Wrap the class for INT and REAL types
5 WRAP_IMAGE_FILTER_INT (1)
6 WRAP_IMAGE_FILTER_REAL (1)
7
8 # Wrap the Sigma property
9 BEGIN_MANAGED_PROPERTY ("Sigma" SET)
10   SET (MANAGED_PROPERTY_SUMMARY "Set the Gaussian variance (in image spacing).")
11   SET (MANAGED_PROPERTY_TYPE "double")
12   SET (MANAGED_PROPERTY_SET_BODY "m_PointerToNative->SetSigma( value );")
13 END_MANAGED_PROPERTY ()
14
15 # Wrap the NormalizeAcrossScale property
16 BEGIN_MANAGED_PROPERTY ("NormalizeAcrossScale" GETSET)
17   SET (MANAGED_PROPERTY_SUMMARY "Get/set whether normalization should occur.")
18   SET (MANAGED_PROPERTY_TYPE "bool")
19   SET (MANAGED_PROPERTY_GET_BODY "return m_PointerToNative->GetNormalizeAcrossScale( );")
20   SET (MANAGED_PROPERTY_SET_BODY "m_PointerToNative->SetNormalizeAcrossScale( value );")
21 END_MANAGED_PROPERTY ()
22
23 # End the wrapping
24 END_WRAP_CLASS ()

```

```

1  # Begin the wrapping
2  WRAP_CLASS("itk::Hessian3DToVesselnessMeasureImageFilter")
3
4  # Wrap the template arguments
5  WRAP_TEMPLATE("${ITKM_F}" "${ITKT_F}")
6
7  # Wrap the Alpha1 property
8  BEGIN_MANAGED_PROPERTY("Alpha1" GETSET)
9      SET(MANAGED_PROPERTY_SUMMARY "Get/set alpha1.")
10     SET(MANAGED_PROPERTY_TYPE "double")
11     SET(MANAGED_PROPERTY_GET_BODY "return m_PointerToNative->GetAlpha1( );")
12     SET(MANAGED_PROPERTY_SET_BODY "m_PointerToNative->SetAlpha1( value );")
13 END_MANAGED_PROPERTY()
14
15 # Wrap the Alpha2 property
16 BEGIN_MANAGED_PROPERTY("Alpha2" GETSET)
17     SET(MANAGED_PROPERTY_SUMMARY "Get/set alpha2.")
18     SET(MANAGED_PROPERTY_TYPE "double")
19     SET(MANAGED_PROPERTY_GET_BODY "return m_PointerToNative->GetAlpha2( );")
20     SET(MANAGED_PROPERTY_SET_BODY "m_PointerToNative->SetAlpha2( value );")
21 END_MANAGED_PROPERTY()
22
23 # End the wrapping
24 END_WRAP_CLASS()

```

We point CMake at this folder, choose a build directory, and configure the project for Visual Studio 8¹. ManagedITK should create the relevant files, including a `FinishCMake.bat` file which must be run *before* opening the solution file and compiling the project. The output will be a single executable `ManagedITK.Filtering.Vesselness.dll`.

The next step is to create a Python script for use with SharpImage (see `source/vesselness/Vesselness.py`):

```

1  #=====
4  # Module:      Vesselness.py
17 #=====
18
19 # Import the base script class
20 import ImageToImageScript
21 from ImageToImageScript import *
22
23 # Add CLR reference and import required libraries
24 clr.AddReference("ManagedITK.Filtering.Vesselness")
25 from itk import *
26
27 class VesselnessScript(ImageToImageScriptObject):
28     # -----
29     Name = "Vesselness"
30     Help = """Implements a Hessian-based line enhancement filter for segmenting\r\
31         tubular objects. The input image must be a 3-D image."""
32
33     Sigma = 1.0
34     Alpha1 = 0.5
35     Alpha2 = 2.0
36     NormalizeAcrossScale = False
37     # -----
38
39     def ThreadedDoWork(self):
40         """ Perform the main functions of the script on a background thread. """
41         try:
42             # Start

```

¹We have not tried Visual Studio Express Edition, so there may be issues if you are using that specific compiler.

```

59         self.StartedWork()
60         self.WriteInputName()
61
62         # Compute hessian
63         filterHessian = itkHessianRecursiveGaussianImageFilter.New( self.Input )
64         self.AddEventHandlersToProcessObject( filterHessian )
65         filterHessian.SetInput( self.Input )
66         filterHessian.Sigma = self.Sigma
67         filterHessian.NormalizeAcrossScale = self.NormalizeAcrossScale
68
69         # Compute vesselness
70         filterVesselness = itkHessian3DToVesselnessMeasureImageFilter.New( itkPixelType.F )
71         self.AddEventHandlersToProcessObject( filterVesselness )
72         filterVesselness.SetInput( filterHessian.GetOutput() )
73         filterVesselness.Alpha1 = self.Alpha1
74         filterVesselness.Alpha2 = self.Alpha2
75         filterVesselness.UpdateLargestPossibleRegion()
76         filterVesselness.GetOutput( self.Output )
77
78         # Clean up and finish
79         self.DisconnectInputAndOutput()
80         self.DisposeOfObject( filterHessian )
81         self.DisposeOfObject( filterVesselness )
82         self.WriteOutputName()
83         self.FinishedWork( True )
84
85     except Exception, ex:
86         self.HandleException( ex )
87         self.FinishedWork( False )
88         self.Finalise()

```

These files (ManagedITK.Filtering.Vesselness.dll and Vesselness.py) must be copied to the SharpImage Scripting folder (we recommend creating a subfolder called SharpImage/Scripting/Custom or similar). A pre-compiled version of the ManagedITK assembly is provided with this article if you wish to bypass this step (see results/ManagedITK.Filtering.Vesselness.dll).

2.2 Fragment Shader

We implement a derivation of the tagged volume rendering method described by Hadwiger et al. [2]. In their original method tags represent exact objects, which requires tri-linear interpolation and complex boundary filtering to avoid artefacts and improve resolution. Our application allows us to make a different assumption: a tag is a mask guaranteeing to *include* structures of interest, but not *exactly* delineate them. We can therefore use nearest neighbour interpolation and a stack of value-magnitude transfer functions to refine the structures inside the tags (ie. a 3-D texture, similar to Svakhine et al. [11, Sec. 3]). The tagged transfer function is implemented using OpenGL Shading Language (GLSL) (see source/fragment-shader/shader-vmt-phong.frag):

```

1  //=====
4  // Module:      shader-vmt-phong.frag
17 //=====
18 uniform sampler3D sam3Tex0;      // Sampler for transfer function
19 uniform sampler3D sam3Tex1;      // Sampler for value image
20 uniform sampler3D sam3Tex2;      // Sampler for gradient image
21 uniform sampler3D sam3Tex3;      // Sampler for tags image
22 varying vec3 pos3Tex1;          // Current coord of value image

```

```

23 varying vec3 pos3Tex2;           // Current coord of gradient image
24 varying vec3 pos3Tex3;           // Current coord of tags image
96
97 void main()
98 {
99     // Interpolate images
100     float value = vec4( texture3D(sam3Tex1, pos3Tex1) ).a;
101     float gradmag = vec4( texture3D(sam3Tex2, pos3Tex2) ).a;
102     float tags = vec4( texture3D(sam3Tex3, pos3Tex3) ).a;
103
104     // Interpolate transfer function
105     const float fNumLayers = 4.0;
106     vec3 pos3TfAll = vec3( value, 1.0-gradmag, 0.0 );
107     vec3 pos3TfTag1 = vec3( value, 1.0-gradmag, 1.0/(fNumLayers-1.0) );
108     vec3 pos3TfTag2 = vec3( value, 1.0-gradmag, 2.0/(fNumLayers-1.0) );
109     vec4 val4TfAll = texture3D( sam3Tex0, pos3TfAll );
110     vec4 val4TfTag1 = texture3D( sam3Tex0, pos3TfTag1 );
111     vec4 val4TfTag2 = texture3D( sam3Tex0, pos3TfTag2 );
112
113     // Adjust alpha for sampling rate
114     val4TfAll.a = adjustAlphaForSamplingRate( val4TfAll.a );
115     val4TfTag1.a = adjustAlphaForSamplingRate( val4TfTag1.a );
116     val4TfTag2.a = adjustAlphaForSamplingRate( val4TfTag2.a );
117
118     // Mix tags
119     bool light, enhance;
120     vec4 val4Mix;
121     if (val4TfAll.a == 0 && tags > 0.5)
122     {
123         // Tag 2
124         val4Mix = val4TfTag2;
125         enhance=true; light=true;
126         if (val4TfTag2.a <= 0.0) discard;
127     }
128     else if (val4TfAll.a == 0 && tags > 0.25)
129     {
130         // Tag 1
131         val4Mix = val4TfTag1;
132         enhance=true; light=true;
133         if (val4TfTag1.a <= 0.0) discard;
134     }
135     else
136     {
137         // All
138         val4Mix = val4TfAll;
139         enhance=true; light=true;
140         if (val4TfAll.a <= 0.0) discard;
141     }
142
143     // Compute the normal
144     vec4 vec4G = gradientFromCentralDifferences( );
145     vec4 vec4N = normalize( vec4G );
146
147     // Apply lighting
148     if (light)
149         gl_FragColor = val4Mix * phong( vec4N, gl_LightSource[0] );
150     else
151         gl_FragColor = val4Mix;
152 }

```

3 Commands

This section lists the SharpImage commands required to reproduce our results. You will need a good desktop computer with *at least 2 GB RAM* and a recent graphics card with *at least 512 MB VRAM* (you will receive memory allocation errors otherwise). For this experiment we used an Intel Pentium D, 2×3.0 GHz processors, 2 GB RAM, NVIDIA GeForce 8800 GTX, 768 MB VRAM. We assume the data has been unzipped to `C:/Temp`, along with `source/commands/A-SPHERES.txt`. The full list of commands can be found in `source/commands/commands.txt`.

3.1 Orient and Resize

Because our data came from various sources, we found it desirable to orient the images to the same anatomical position. Much of the processing is undertaken on subsampled images, so we also resize the image at this point.

```
2 > Open "C:/Temp/A.mhd#SS3"
3 > Orient Given="RPI" Desired="ASL"
4 > Properties Origin=itkPoint(0,0,0)
5 > Save "C:/Temp/A-ASL.mhd"
6 > CastToF
7 > Resize OutputSize=itkSize(256,256,256) Interpolator="Linear"
8 > Save "C:/Temp/A-ASL-SMALL.mhd"
9 > Close
```

3.2 Speed Function

We now compute the edge-based speed function:

```
12 > Open "C:/Temp/A-ASL-SMALL.mhd#F3"
13 > CurvatureFlow TimeStep=0.1 Iterations=10
14 > Threshold Lower=-2000 Upper=100 OutsideValue=100
15 > ConnectedThreshold Lower=60 Upper=100
17 > Rename "Sternum"
18 > BinaryPixelMath Operation="Add" Input1="Threshold" Input2="Sternum"
19 > LevelSetSpeed OutputMinimum=0.0
28 > Save "C:/Temp/A-ASL-SMALL-SPEED.mhd"
29 > Close
```

The seed for the region growing can be anywhere in the sternum (we used [50, 90, 100]) and the parameters for the speed function were as follows:

```
Gaussian Normalize=False
Gaussian Sigma=0.5
Sigmoid Alpha=-10.0
Sigmoid Beta=10.0
```

```
Threshold Lower=-250.0
Threshold Upper=355.0
Rescale OutputMinimum=000.000
Rescale OutputMaximum=001.000
```

3.3 Initial Contour

The initial contour could be computed from a set of points or — as we prefer — from a set of spheres generated using a 3-D interface:

```
32 > Open "C:/Temp/A-ASL-SMALL.mhd#SS3"
33 > BinaryThreshold Lower=-250 Upper=2000
34 > CastToUC
35 > GenerateMaskFromFile "C:/Temp/A-SPHERES.txt"
36 > BinaryPixelMath Operation="Mask" Input1="Cast" Input2="Mask"
37 > MorphologicalOpen Operation="Binary" KernelRadius=itkSize(4,4,4)
38 > Save "C:/Temp/A-ASL-SMALL-INITIAL.mhd"
39 > Close
```

Notice the morphological opening which removes unwanted pulmonary vessels. The list of spheres is defined in `source/commands/A-SPHERES.txt`:

```
Sphere: Center=119,062,100 Radius=48
Sphere: Center=095,085,076 Radius=45
Sphere: Center=068,106,055 Radius=25
Sphere: Center=112,018,126 Radius=54
Sphere: Center=102,075,126 Radius=50
```

3.4 Fast Marching

We now evolve the active contour, extract the contour at a suitable arrival time, and return the tag to full size:

```
42 > Open "C:/Temp/A-ASL-SMALL.mhd#SS3"
43 > Open "C:/Temp/A-ASL-SMALL-INITIAL.mhd#UC3"
44 > Open "C:/Temp/A-ASL-SMALL-SPEED.mhd#F3"
45 > FastMarching InitialImage="Initial" StoppingValue=100.0
46 > MorphologicalErode KernelRadius=itkSize(2,2,2)
47 > BinaryThreshold Lower=0 Upper=14
48 > CastToUC
49 > Resize OutputSize=itkSize(512,373,512) Interpolator="Nearest"
50 > Save "C:/Temp/A-ASL-HEART.mhd"
51 > Close
```


3.5 Vesselness

We now segment the vessels using the script created earlier:

```
54 > Open "C:/Temp/A-ASL-SMALL.mhd#F3"  
55 > Vesselness Sigma=0.7  
56 > ImageRange Minimum=0.0 Maximum=100.0  
60 > CastToUC  
61 > Resize OutputSize=itkSize(512,373,512) Interpolator="Nearest"  
62 > MorphologicalDilate Operation="Binary" KernelRadius=itkSize(2,2,2)  
63 > Save "C:/Temp/A-ASL-VESSELS.mhd"  
64 > Close
```

The `ImageRange` script is required to increase the contrast for selecting the seeds. We specified two seeds for the region growing: one in the left coronary artery (LCA) [95, 122, 169], and one in the right coronary artery (RCA) [126, 86, 96].

3.6 Combine Tags

We are now ready to combine our two tags into a single image:

```
67 > Open "C:/Temp/A-ASL-VESSELS.mhd#UC3"  
68 > Open "C:/Temp/A-ASL-HEART.mhd#UC3"  
69 > ShiftScale Shift=-150  
70 > BinaryPixelMath Operation="Max" Input1="Heart_Shift" Input2="Vessels"  
71 > Save "C:/Temp/A-ASL-TAGS.mhd"  
72 > Close
```

3.7 Histogram

This step is purely optional, but it is often desirable to have a histogram to aid transfer function specification:

```
75 > Open "C:/Temp/A-ASL-SMALL.mhd#F3"  
76 > MorphologicalGradientMagnitude KernelRadius=itkSize(1,1,1)  
77 > ValueEdgeHistogram Value="Small" Edge="Magnitude" NumberOfBins=[512,128]  
78 > Save "C:/Temp/A-ASL-HISTOGRAM.png"  
79 > Close
```

3.8 Volume Render

The preparation is now complete and we are ready to render the volumes:

```

82 > Open "C:/Temp/A-ASL-HISTOGRAM.png#UC2 "
83 > Open "C:/Temp/A-ASL-TAGS.mhd#UC3 "
84 > Open "C:/Temp/A-ASL.mhd#SS3 "
85 > MorphologicalGradientMagnitude KernelRadius=itkSize(1,1,1)
86 > RescaleIntensityToUC
87 > VolumeRender Value="A-ASL.mhd" Gradient="Rescale" Tags="Tags"
88     Tf=siTransferFunction(itkSize(512,128),"All","Heart","Vessels")

```

Select the “Renderer Editor” and configure the “FragmentProgramPath”. Select the “Transfer function editor” and right-click on the transfer function to add components similar to those shown in the results section.

4 Results

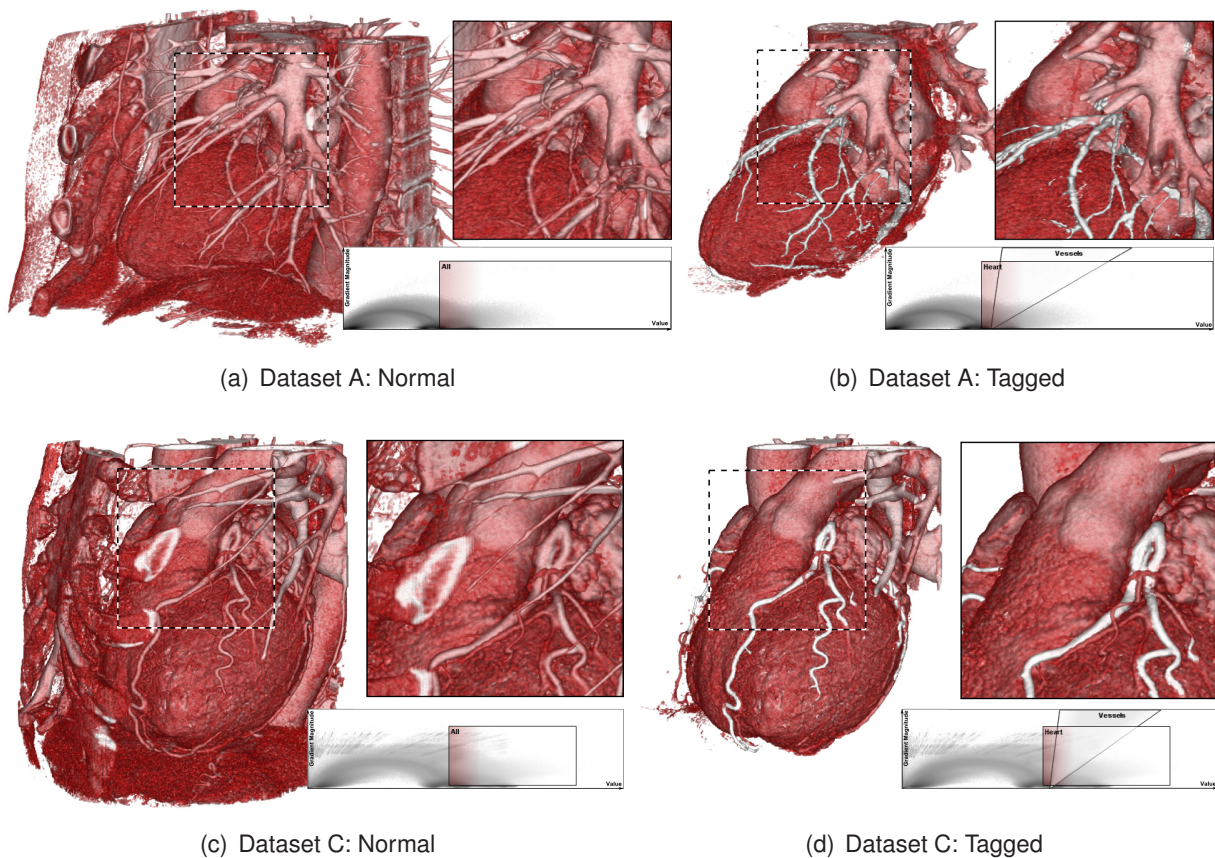


Figure 1: Resultant images using the normal and tagged volume rendering approaches. Dataset A is provided with this article.

5 Conclusion

We have presented a method for tagged volume rendering of the heart. The method is comprised of two stages: offline segmentation of the coronary arteries and pericardial cavity; followed by the online application of value-magnitude transfer functions to refine the tags. The method was presented using the SharpImage prototyping environment which made the steps somewhat involved, but easily reproduced. Feel free to contact us with any questions or suggestions².

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