# BUILDING AN ASSURANCE CASE FOR AORTA GEOMETRY RECONSTRUCTION SOFTWARE

# BUILDING AN ASSURANCE CASE FOR AORTA GEOMETRY RECONSTRUCTION SOFTWARE

BY

JINGYI LIN, M.Eng.

A Report

submitted to the Department of Computing and Software

and the School of Graduate Studies

of McMaster University

in partial fulfilment of the requirements

for the degree of

Masters of Engineering

Masters of Engineering (2023) McMaster University

(Department of Computing and Software) Hamilton, Ontario, Canada

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| TITLE: | Building an Assurance Case for Aorta Geometry Reconstruction Software |
| AUTHOR: | Jingyi Lin<br>M.Eng. (Computing and Software CRP),<br>McMaster University, Hamilton, Canada |
| SUPERVISOR: | Smith Spencer |
| NUMBER OF PAGES: | xvii, 115 |

# Abstract

Assurance cases have been proven to be effective developing a real-time system software. Another domain that requires the high standard correctness, completeness, and consistency is medical software.

Throughout the development of the Aorta Geometry Reconstruction software, we implicitly listed the evidences that are essential to build our confidence in the software for assurance cases, build the artifact and the evidences simultaneously.

Finally, we present this software with the list of the evidences built for assurance cases, to show that the assurance cases can apply well on the medical software

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# Acknowledgements

I would like to thank all the people who contributed in some way to the work described in this thesis.

First and foremost, I would like to express my sincere thanks and gratitude to my supervisor Dr. Spencer Smith for his motivation, patience, and the continuous support of my master's studies and research. His guidance helped me in all the time of research and writing of this thesis.

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# Notation, Definitions, and Abbreviations

## Definitions

**Aorta** The aorta is the largest artery of the body and carries blood from the heart to the circulatory system. It has several sections: the aortic root is the transition point where blood first exits the heart. It functions as the water main of the body, the aortic arch, is the curved segment that gives the aorta its cane-like shape. It bridges the ascending and descending aorta. Throughout the documentation, aorta would only include ascending aorta, aortic arch and descending aorta. Abdominal aorta is outside of the scope of the current work.

**Ascending Aorta**

The ascending aorta is the first part of the aorta, which is the largest blood vessel in the body. It comes out of your heart and pumps blood through the aortic arch and into the descending aorta.

**Descending Aorta**

The descending aorta is the longest part of your aorta (the largest artery in your body). It begins after your left subclavian artery branches from your aortic arch, and it extends down into your belly. The descending aorta runs from your chest (thoracic aorta) to your abdominal area (abdominal aorta).

**Organ Segmentation**

The definition of the organ boundary or organ segmentation is helpful for the orientation and identification of the regions of interest inside the organ during the diagnostic or treatment procedure. Further, it allows the volume estimation of the organ, such as the aorta.

**DICOM** Digital Imaging and Communications in Medicine (DICOM) is the standard for the communication and management of medical imaging information and related data.

**Inferior** Inferior is the direction away from the head; the lower (e.g., the foot is part of the inferior extremity).

**Superior** Superior is the direction toward the head end of the body; the upper (e.g., the hand is part of the superior extremity).

**Slice** A 2-dimensional image is retrieved from a 3-dimensional volume.

**Binary Dilation**

Binary dilation is a mathematical morphology operation that uses a structuring element (kernel) for expanding the shapes in an image.

**Label Map** A labeled map or a label image is an image that labels each pixel of a source image.

**Euclidean Distance Transform**

The euclidean distance transform is the map labeling each pixel of the image with the distance to the nearest obstacle pixel (black pixel for this project).

**Contour Line** A contour line (also isoline, isopleth, or isarithm) of a function of two variables is a curve along which the function has a constant value so that the curve joins points of equal value.

**Level Sets** Level Sets are an important category of modern image segmentation techniques based on partial differential equations (PDE), i.e. progressive evaluation of the differences among neighboring pixels to find object boundaries. The pictures 2.4 demonstrate an example of how Level Sets method work on finding the region of the heart. It starts with a seed contour that is within the region of interest, then by finding the gradient based on the contour line, the segmentation result will propagate towards outside of the region until the maximum difference between the neighboring pixels are reached.

**Segmented slice**

A 2-dimensional image with interested pixels labeled as 1 and other pixels as 0.

**Kernel Size** The size of the kernel for binary dilation.

**Stop Limit** This limit is used to stop the segmentation algorithm. It is used differently in segmentation in inferior direction and segmentation in superior direction.

**Threshold Coefficient**

This coefficient is used to compute the lower and upper threshold passing through the segmentation filter SITK's ThresholdSegmentationLevelSetImageFilter. The algorithm first uses SITK's LabelStatisticsImageFilter to get the mean and the standard deviation of the intensity values of the pixels that are labeled as the white pixel. Larger values with this coefficient imply a larger range of thresholds when performing the segmentation, which leads to a larger segmented region.

**RMS Error** Value of RMS change below which the filter should stop. This is a convergence criterion.

**Maximum Iteration**

Number of iterations to run

**Curvature Scaling**

Weight of the curvature contribution to the speed term.

**Propagation Scaling**

Weight of the propagation contribution to the speed term.

# Abbreviations

| | |
|---|---|
| **AC** | Assurance Case |
| **AGR** | AortaGeomRecon |
| **AortaGeomRecon** | 3D Slicer's extension module, Aorta Geometry Reconstruction |
| **CT** | computerized tomography |
| **DD** | Design Document |
| **DICOM** | Digital Imaging and Communications in Medicine |
| **MG** | Module Guide |
| **SITK** | SimpleITK |
| **SRS** | Software Requirements Specification |
| **VTK** | The Visualization Toolkit |

# Declaration of Academic Achievement

The student will declare his/her research contribution and, as appropriate, those of colleagues or other contributors to the contents of the thesis.

# Chapter 1

# Introduction

Medical Software is a critical component of patient diagnosis and treatment. Medical software refers to computer programs, applications, or systems specifically designed for use within the healthcare and medical field. These software solutions are developed to assist healthcare professionals, researchers, administrators, and patients in various aspects of medical care, research, management, and education [20]. Our project focuses on medical software that wields a direct and crucial influence on patients' well-being, particularly software that contributes to diagnosing issues related to the aorta. The aorta, a vital organ responsible for transporting blood from the heart to other bodily organs, holds immense significance. Any malfunction in its blood-carrying function could yield severe and potentially life-threatening consequences for the entire body's physiology. Our objective centers around the Aorta Geometry Reconstruction (AortaGeomRecon or AGR) software, which can build the 3-dimensional model of the aorta, to help the health professional disagnosing issues related to the aorta quickly and correctly.

Given the importance of medical software like AGR, we need a means to build

confidence in the software. In this report, we explore the use of assurance cases. An assurance case can be thought of as a specific type of argumentation used in various cases. The main purpose of an assurance case is to establish confidence and trust in the reliability and safety of a system by presenting a well-structured argument supported by evidence [21]. Assurance cases have been applied regularly in the medical device for approval in U.S. In Europe, the assurance cases are required in systems as diverse as flight control systems, nuclear reactor shutdown systems, and railroad signaling systems, which are all critical systems [21]. Previous works [18] building assurance cases for scientific computing software such as 3dfim+, a medical imaging software analysing activity in the brain, has demonstrated a great success in showing the software's correctness and reliability. The motivation of our project is to build an assurance case for AGR by adding more details on the evidence needed to support our claim, thus building our confidence in AGR.

In this chapter, we first explain in details the contexts for the key concepts that will be discussed throughout the document, including what is organ segmentation, what is aorta, listing the diseases that aorta segmentation could detect, and demosntrates an example of assurance case by showing a simple diagram of assurance case. Next, we will briefly discuss on the methodology, especially how we achieved the objective of design, implementation of the software, and building confidence with the evidences in assurance cases. In the final section, we will explain our thesis outline covering the entire report.

## 1.1 Background

In this section, we present some contexts on the key concepts within the scope of our work.

### 1.1.1 Aorta

Aorta is the largest artery that carries blood from the heart to the circulatory system. It has a cane-liked shape with ascending aorta, aortic arch and descending aorta. Figure 1.1 shows the entired aorta, but abdominal aorta is outside of the scope of the current work. Our work focus on building the 3D geometry from aortic root to descending aorta.

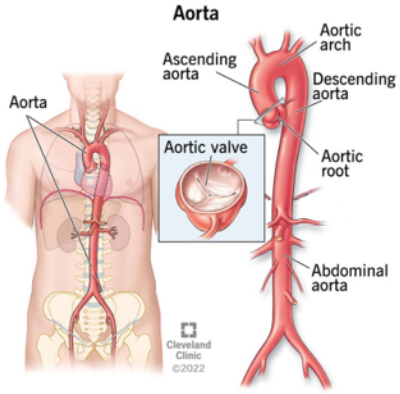



Figure 1.1: Aorta

### 1.1.2 Organ Segmentation

The definition of the organ boundary or organ segmentation is helpful for the orientation and identification of the regions of interest inside the organ during the diagnostic or treatment procedure. Further, it allows the volume estimation of the organ, such

as the aorta. Figure 1.2 demonstrates an example of abdominal organ segmentation.

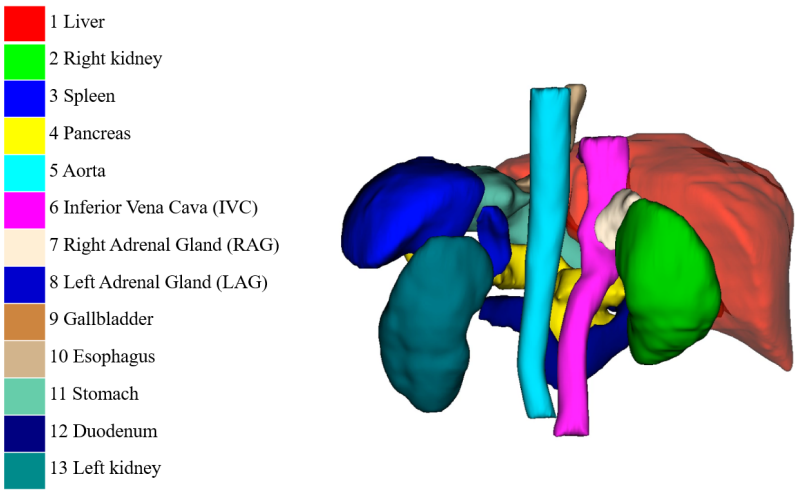



Figure 1.2: Organ Segmentation [16]

Aorta segmentation in computerized tomography (CT) scans is important for:

- Coarctation of the aorta
- Aortic Aneurysm
- Aortic calcification quantification
- To guide the segmentation of other central vessels.

### 1.1.3 Assurance Case

An Assurance Case (AC) can be thought of as a specific type of argumentation used in various cases. When building an AC, you're making a point that specific evidence backs up a particular statement. The fundamental structure is depicted in Figure 1.3.

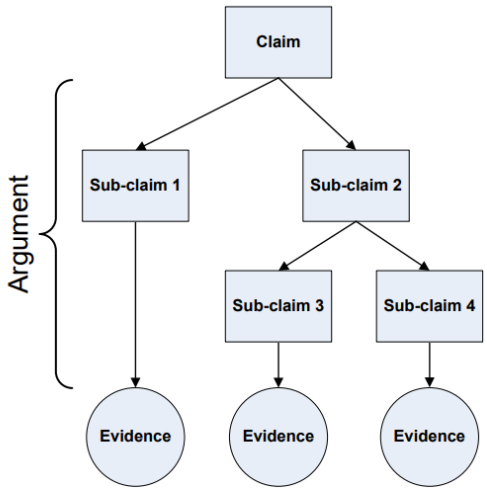



Figure 1.3: Simple Assurance Case Diagram [4]

So, an AC essentially boils down to an organized collection of arguments, backed by a body of evidence, that helps validate the belief in a specific claim [4].

In a practical sense, creating an AC involves beginning with a main claim and then breaking it down into smaller claims through a step-by-step process. These smaller claims, at the most bottom, are supported by concrete evidence.

## 1.2 Methodology

In this study, we present the outcomes of integrating AC throughout the development of medical software to reinforce stakeholders' confidence in the software's capabilities. The software, known as AortaGeomRecon (AGR), represents a 3D Slicer [11] extension module designed to semi-automatically construct a 3D model of the aorta using CT scans from a patient's chest. We started by gathering requirements for the AGR from a domain expert, drafted our Software Requirements Specification (SRS), and

Module Guide (MG). We researched and worked on the implementation of the software, while building the infrastructure for continuous integration, version control, and project managment using GitHub. When we have a functional prototype, we delved into our assurance cases, encompassing chosen arguments and supporting evidence. AC functions as a method to provide assurance for a system by presenting arguments that substantiate claims about the system. These arguments are based on evidence related to the system's design, development, and tested behavior. By constructing AC, we were able to follow the best practice including documentation review on SRS and MG to finalize our documentation, ensure the documentation's completeness and correctness. We have built a user documentation to define all operational assumptions, and guide user to use the valid inputs with a sequence of correct operations. Finally, our continuous integration tests, code review, and several algorithm reviews reinforced our confidence in the implementation of the software, which has strickly complying with the requirements that are complete and correct.

## 1.3 Thesis Outline

The thesis is organized into three broad parts. In Chapter 2, we introduce our program AortaGeomRecon by mentioning the existing methods, the AGR's algorithm overview and step by step workflow. We explain necessary terms and information to understand how the software functionsfinally, and the 3D Slicer [11] extension module that the user interacts with to get the segmentation result with our algorithm. In Chapter 3, we present our AC and focusing on the evidence, including some sections of our SRS, Design Documents, Module Guide, Algorithm Review, and a test case we developed for verifying and validating the correctness of program AGR. In Chapter

4, future work is proposed and conclusions are drawn based on the developed SRS, segmentation algorithm, 3D Slicer module extension, and AC.

# Chapter 2

# AortaGeomRecon Research and Development

This chapter will discuss the research and development of the 3D Slicer plugin AGR.

AortaGeomRecon stands for Aorta Geometry Reconstruction. The main objective of this software is to semi-automatically build the 3D geometry of the aorta from the patient's chest CT scans. The existing methods often involved of extensive manual steps work interspersed with software assistance. An experienced user, who should be a medical domain expert typically needs to do a minimum of 10 minutes of manual work. Current AGR allows users who have taken the university level anatomy introduction courseto set the hyperparameters within half a minute,following by a maximum 2 minutes of execution time.

In this chapter, we first introduce the existing methods with different softwares to perform the aorta segmentation, and discuss their advantages and disadvantages. Then, we demonstrate our segmentaiton algorithm, with a detailed step-by-step explanation of what the algorithm is doing and the result it generates. Finally, we discuss

our experience using the platform 3D Slicer, and demonstrate our development result in 3D Slicer plugin.

## 2.1 Existing Methods

There are many segmentation software options available to users. We will discuss two popular software options: ITK-Snap and 3D Slicer.

### 2.1.1 ITK-Snap bubble method

ITK-Snap provides a segmentation method that first requires the user to select multiple voxels with a custom initial size and an expanding size within the volume. This method is referred to as the "bubble method" [6].

Through many iterations, the voxels expand to fill the entire volume of the vessel. As a final step, the user will need to cut off the extra parts of the volume. Figure 2.1 shows ITK-Snap UI executing a segmentation of an aorta.

The advantages of the bubble method is that it is guaranted to produce a correct segmentation result for a valid image. A medical domain expert can manually control the wanted area, and visually observe the segmentation result expanding, shrinking. Moreover, the user can erase the unwanted parts.

The disadvantages of this method is that the operations described above are complicated. They are easier to say then do. An operator who has previous experience building the geometry with this method still needs about 20 minutes of manual work to build a new aorta geometry. Plus, ITK-Snap software can only read VTK (The Visualization Toolkit) file; therefore, the chest CT scans that are usually Digital Imaging

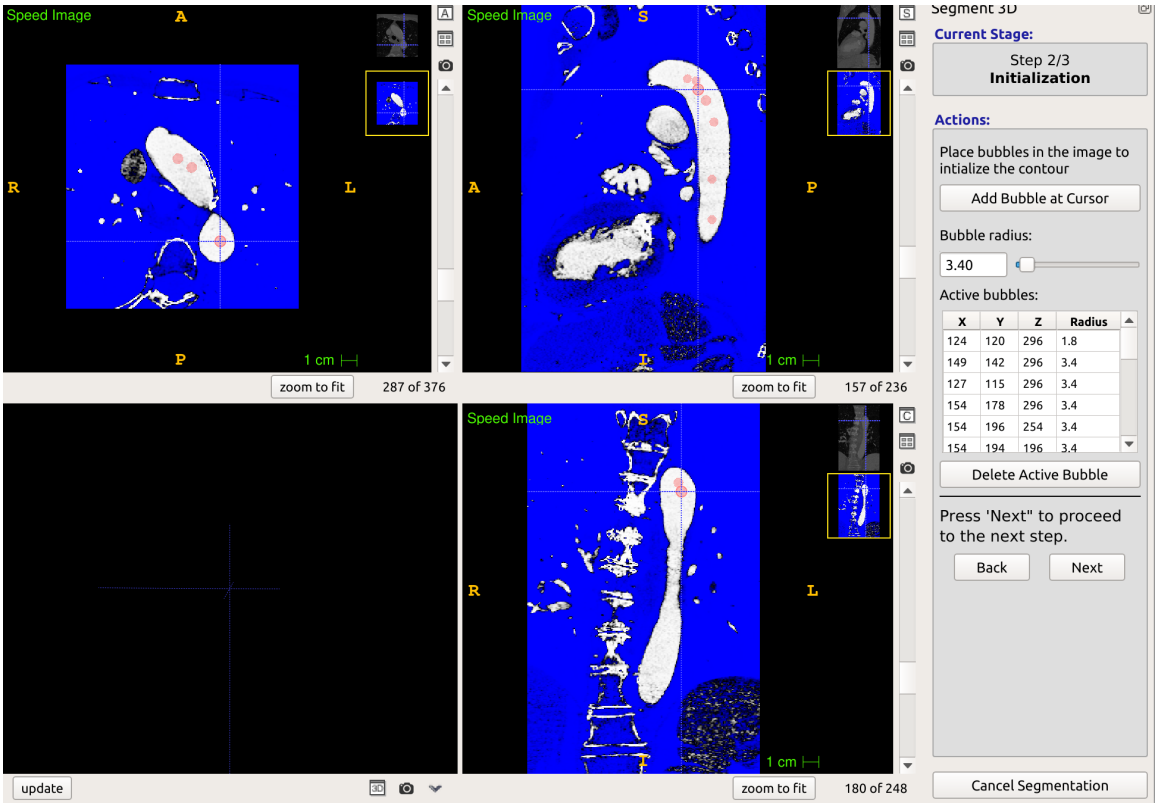



Figure 2.1: ITK-Snap's Bubble Segmentation UI [23]

and Communications in Medicine (DICOM) format [7], needed a manual conversion before using this software and its segmentation method.

### 2.1.2 3D Slicer threshold segmentation

3D Slicer is another well-known medical image processing software for academic uses. 3D Slicer provides multiple segmentation methods [1]. One of the quickest and easiest to use is the intensity based segmentation.

This method first lets users select a small area that belongs to the wanted area on a 2D plane (Axial, Sagittal, and Coronal). 3D Slicer read the pixels' intensity of the surrounding area, and segments based on the intensity threshold. Any pixel's

intensity that is within the range will be segmented as the segmentation result, as demonstrated in Figure 2.2.

Like the bubble method, this method often reads extra volume, and requires the user to cut the unwanted parts. A YouTube video shows an experienced user who gets the aorta 3D geometry with 8 minutes of manual works.

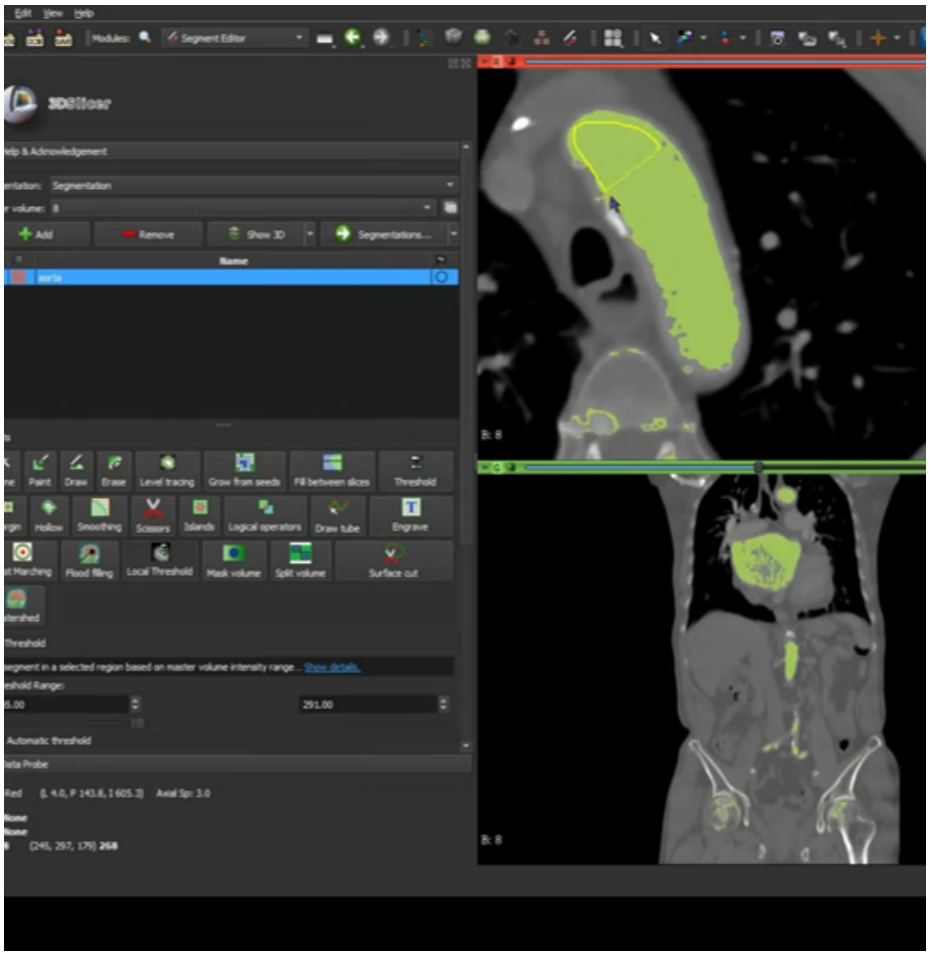



Figure 2.2: 3D Slicer Built-in Segmentation Method [11]

## 2.2 Segmentation Algorithm

This section introduces the key concepts of the implementation on the segmentation algorithm. The algorithm is developed in Python with the external libraries SimpleITK and NumPy. The algorithm builds the 3D Aorta geometry by doing segmentation on each axial slice. The logic behind segmenting each slice from the axial view, is that there is one or two circles that is edged bounded in each axial plane view. Using this information, and given an initial aorta center coordinate, the algorithm continuously segments each axial's slice circles closest to the previous aorta center coordinates. Finally, some hyperparameters tuning can let the algorithm pick up the pixels that were missing but belongs to the part of the aorta.

In this section, we first introduces the contexts for exertal libraries used in the implementation of the algorithm. We show the parameters and hyperparameters of the algorithm. Then we explain the algorithm workflow with a step-by-step demonstration.

### 2.2.1 Background

SimpleITK is an open-source multidimensional image analysis library developed by the Insight Toolkit community for the biomedical sciences and beyond [3][15]. NumPy is the fundamental package for scientific computing with Python, especially for the performance of multidimensional array processing [9]. The algorithm will use functions from these two libraries for image processing and multidimensional array processing. For example, the algorithm segments each slice with ThresholdSegmentationLevelSetImageFilter from SITK.

The algorithm works best with the chest volume cropped to a rectangular prism

that contains the aorta and parts of the other organs such as the backbone, blood vessels, and the heart. This can be done with 3D Slicer and its built-in modules, Volume rendering and Crop Volume, or researched by the user to find the starting point and the size to crop.

### 2.2.2 Parameters

At the beginning of the algorithm, the user inputs two integer coordinates indicating the position of the descending aorta and ascending aorta center on a single slice. The yellow dots in Figure 2.3 shows an example of the aorta seeds. These seeds will be updated by the algorithm after processing each axial plane.

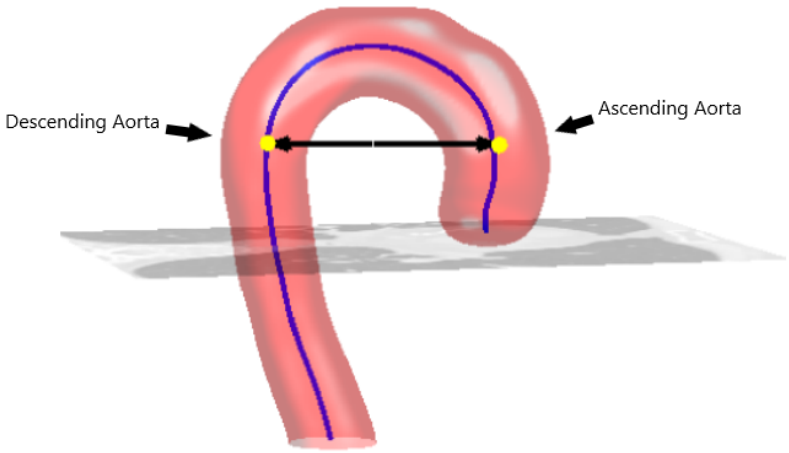



Figure 2.3: The aorta seeds [13]

The following list of hyperparameters that can be tuned to get the best segmentation result:

- The stop limit, which controls the stop condition

- The threshold coefficient, which controls the segmentation acceptable intensity range
- The kernel size, which controls the label image circle size
- The threshold Segmentation Level Sets Image Filter parameters, including:
  - The RMS error
  - The maximum iteration
  - The curvature scaling
  - The propagation scaling

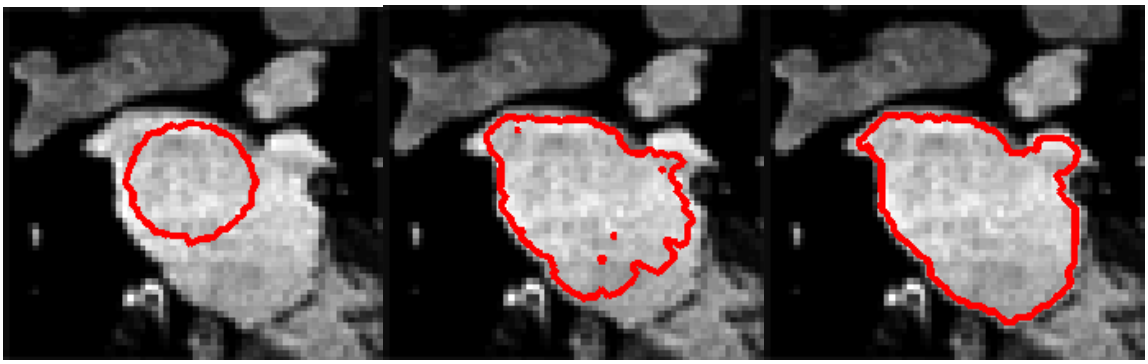
One of the most important parameters is the threshold coefficient. Since the algorithm segments based on the intensity of the gray scale pixels, decreasing the threshold coefficient decreases the acceptable range of the pixels, and vice-versa.

### 2.2.3 Algorithm Overview

When the user has selected the aorta seeds, the plane where the aorta seeds are located is the initial plane. From this plane towards the bottom (toward the feet) is the inferior direction. The upward direction (toward the head) is the superior direction. This algorithm segments each slice with SITK::ThresholdSegmentationLevelSetImageFilter. The principles of this image filter can be explained with two terms: Level sets segmentation method, and a threshold range that defines the intensity of the acceptable pixel.

Level Sets are an important category of modern image segmentation techniques

based on partial differential equations (PDE), i.e. progressive evaluation of the differences among neighboring pixels to find object boundaries. The pictures 2.4 demonstrate an example of how the Level Sets method work on finding the region of the heart. It starts with a seed contour that is within the region of interest, then by finding the gradient based on the contour line, the segmentation result will propagate towards the outside of the region, until the maximum difference between the neighboring pixels are reached.



(a) Init image (b) Expanding (c) Result

Figure 2.4: Level Sets Segmentation

### 2.2.4 The steps to segment a single slice

In the following section, we will present each step to segment a single slice. These steps are applied in segmentations in both the superior and inferior directions. There is a difference in the stopping condition, which we will elaborate in the following section 2.2.4.6.

#### 2.2.4.1 Create A Label Map

The algorithm uses SITK::BinaryDilateImageFilter to perform binary dilation to generate a circle-like shape around the center coordinates (user input's for the first slice and calculated by the algorithm for the rest of the slices). Each pixel within this shape will be labeled as a white pixel (value of 1), and the rest of the pixels are labeled as black pixels (value of 0).

The generated result is the label map image, and we will use it in the next few steps. The size of the circle-like shape is determined by the kernel size (user's input). The Figure 2.5 shows an example of generated label map image (the green parts) overlay over the original slice.

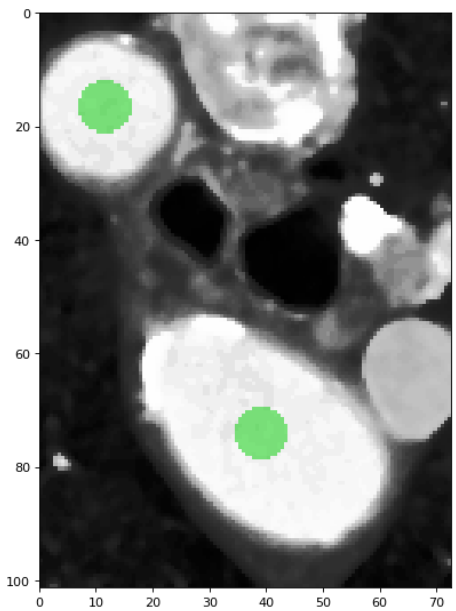



Figure 2.5: A Label Map

#### 2.2.4.2 Create A Distance Map

With SITK::SignedMaurerDistanceMapImageFilter, the algorithm creates another image, the Euclidean distance transform of the label image from previous step. This is used as a contour line that helps build the gradient mentioned in Level sets. The Figure 2.6 shows an example of distance map.

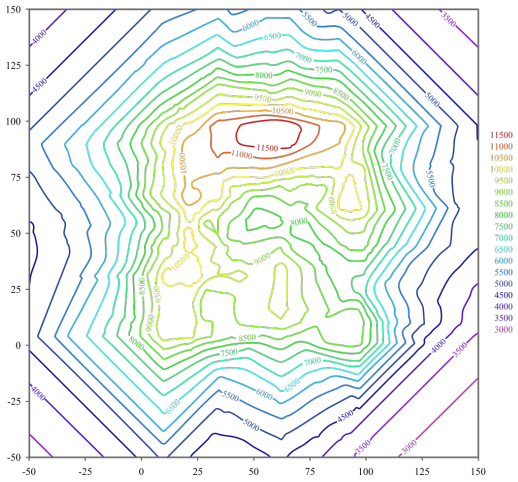


Figure 2.6: A Distance Map

#### 2.2.4.3 Calculate A Threshold Range

By using SITK::LabelStatisticsImageFilter, the algorithm gets the mean and the standard deviation of the intensity values of the pixels that were labeled as the white pixel in the label map. The algorithm uses the threshold coefficient to calculate the lower and upper threshold to be used in the next step.

```
intensity_mean = self._stats_filter.GetMean(
    PixelValue.white_pixel.value)
std = self._stats_filter.GetSigma(PixelValue.white_pixel.value)
lower_threshold = (intensity_mean - self._threshold_coef*std)
upper_threshold = (intensity_mean + self._threshold_coef*std)
self._segment_filter.SetLowerThreshold(lower_threshold)
self._segment_filter.SetUpperThreshold(upper_threshold)
```

Figure 2.7: Code That Shows How To Calculate The Threshold Range

#### 2.2.4.4 Segment A Single Slice

With SITK::ThresholdSegmentationLevelSetImageFilter, the seed image calculated in step 2.2.4.2, and the lower and upper threshold value calculated in step 2.2.4.3, the algorithm performs segmentation and generates a segmented slice. The Figure 2.8 shows an example of generated segmented slice (the green parts) overlay over the original slice.

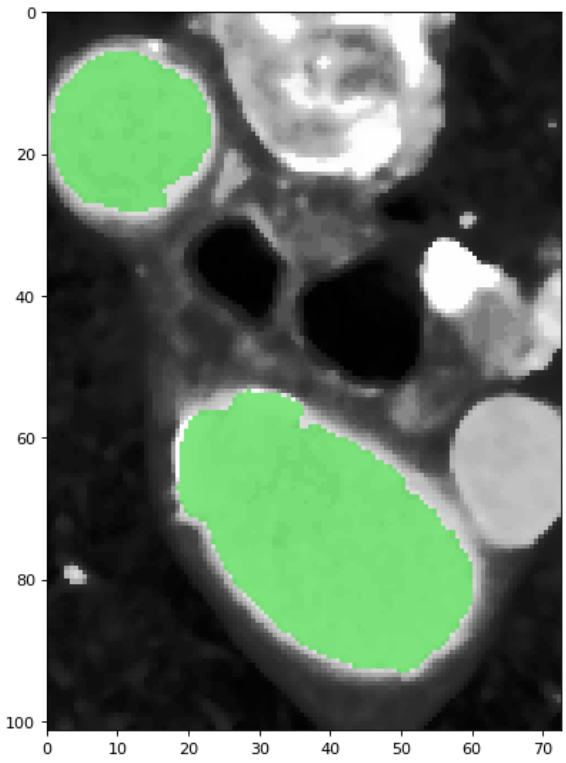



Figure 2.8: A Segmented Image On Top Of The Original Slice

#### 2.2.4.5 Calculate New Centroids

By comparing each pixel segmented as aorta to the previous descending centroid and the previous ascending centroid, the algorithm use the positions of the points closer

to the previous descending centroid to calculate the new descending aorta centroid, and vice-versa for the ascending aorta centroid. However, at certain points during the segmentation in the inferior direction, the slice might reach the end of the ascending aorta, the aortic root, the algorithm will stop using and calculate ascending aorta centroid and only computes descending aorta centroid for the slices afterward.

#### 2.2.4.6 Verify Segmentation Result

There are two main stopping conditions for verifying segmentation result, one condition for the segmentation in the inferior direction and the other one for the segmentation in the superior direction. Stopping limit is a user defined parameter to control the algorithm, to calculate the condition with the centroids position and the standard deviation.

In the inferior direction, if the new ascending aorta centroid that is closest to the previous ascending aorta center is reaching the distance limit, then the algorithm will stop and consider taking the new centroid closer to the ascending aorta. In other words, only 1 centroid will be used for descending aorta segmentation.

In the superior direction, if the standard deviation of the initial label map and the segmentation result label map have larger differences than the limit, the algorithm will stop processing segmentation for the rest of the slices. For example, assume that the standard deviation of the initial label image is 20, and the standard deviation of the segmentation label image is 40, with stop limit of 10, the program will halt immediately.

### 2.2.5 Algorithm Summary

Given two integer coordinates, ascending aorta centroid and descending aorta centroid, the algorithm set the inputted plane as the initial plane. From the initial plane to the bottom (toward the feet) plane, the algorithm calculates a label map with two centroid coordinates and kernel size, calculates a distance map with the label map, calculates a threshold range with the label map's selected pixels, performs segmentation, calculates new centroid coordinates, and verifies the segmentation result in case that it reaches the stop condition. Once the algorithm finishes the segmentation in the inferior direction, the algorithm works from the initial plane to the top (toward the head) plane, repeating the similar steps. Each segmentation result slice is stored in a SITK's image, which supports the conversion to VTK file or DICOM file. Figure 2.9 demonstrates a segmentation result, rendering in 3D Slicer.

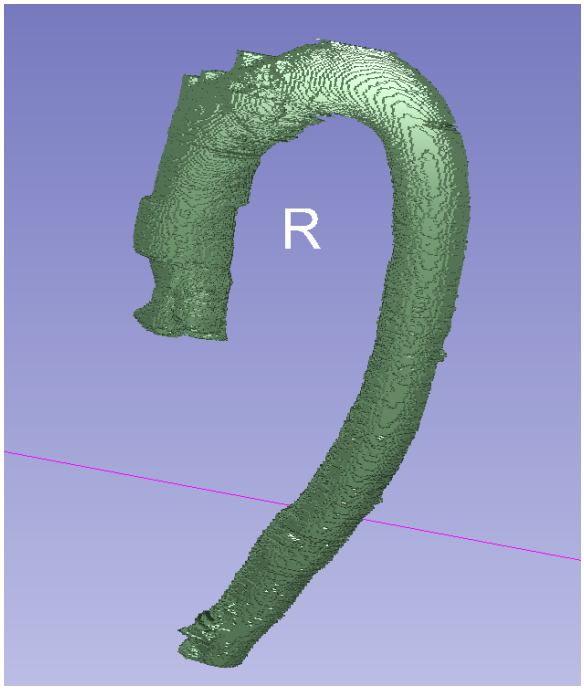



Figure 2.9: Segmentation Result

## 2.3 3D Slicer Extension Development

The project has started with a simple segmentation program build in Jupyter Notebook [12]. When getting a new patient's data, the user will need to investigate the chest CT scans using another software (3D Slicer, ITK-Snap), to get the readings such as coordinates and size to crop (the coordinates of the yellow dots shown in Figure 2.3).

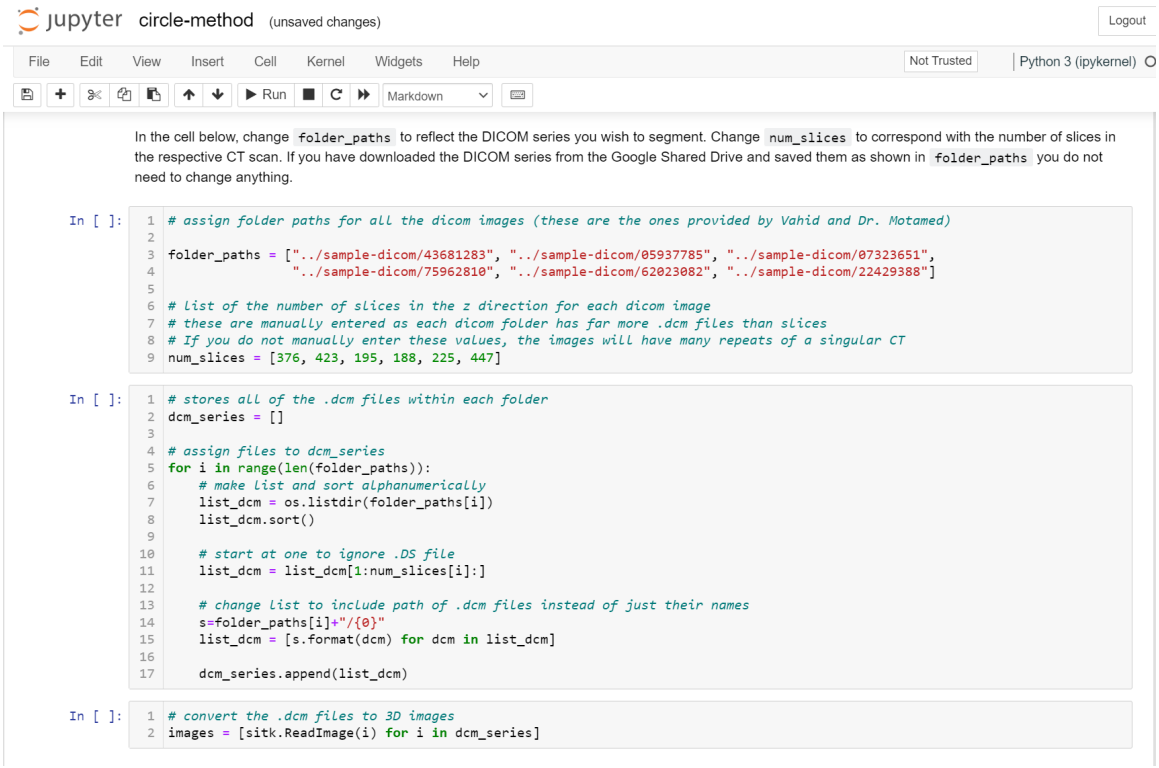



Figure 2.10: Jupyter Notebook Researched by Kailin Chu

Originally, the parameters entered by the users, and many other values are hard-coded in the Jupyter Notebook. To improve the usability of the AortaGeomRecon (reduce the amount of time for user inputs and execution), we implemented an extension module on 3D Slicer.

3D Slicer is an open-sourced medical image processing software for research. 3D Slicer provides useful modules such as Crop Volume module and Volume Rendering module that easily crop any volume. 3D Slicer is highly modulable with Python scripting to control the extension module sequence, and QT designer to generate Graphical User Interfaces.

3D Slicer supports modularization with an extension. An extension can compose multiple modules, where each module is dedicated to solve a sub-problem.

### 2.3.1 3D Slicer's data structure

3D Slicer's Data Structure can be divided into two categories. The Node data structure store large data such as DICOM with a Volume Node, Volume rendering Region of Interest Node, Label Map Volume Node. The parameters are stored as string from the UI component of the module. Every data stored in 3D Slicer can be accessed by the 3D Slicer's Widget Class and Logic Class for further processing.

3D Slicer stores all the above data in a scene object, which is also referred as MRMLscene file, on the higher level data format. 3D Slicer can load any MRMLscene file, this allowed user to retrieve all the data nodes and parameters. On the other hand, 3D Slicer has a special input module, the DICOM database allowed user to store DICOM metadata in 3D Slicer.

### 2.3.2 3D Slicer's scripted module

Every ScriptLoadableModule in 3D Slicer have a Widget Class and a Logic Class. The Widget Class is used to initialize the extension module's UI component, and the parameters tied to the UI component. The module's Logic Class is used to perform

the processing of the data. In the Logic Class, we initialize an AortaGeomRecon Segmenter object with the attributes set to the parameters reading from UI component, which are inputs by the user. After completing the segmentation with Segmenter object, we convert the SimpleITK image object to a volume node corresponding in 3D Slicer, which allow the user to visualize the segmentation result.

### 2.3.3 AortaGeomReconDisplayModule

In this section, we demonstrate the implementation details of the 3D Slicer plugin AGR. We first demonstrate the module's Graphical User Interface, then discuss on the module's logic and workflow.

#### 2.3.3.1 Graphical User Interface

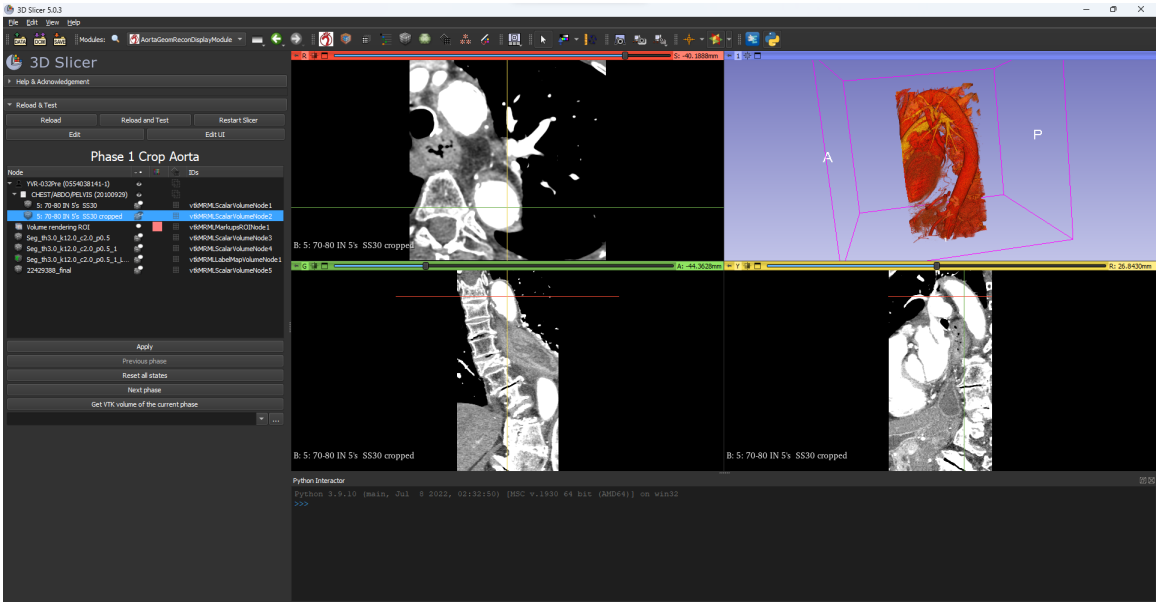



Figure 2.11: 3D Slicer UI

3D Slicer separate the UI into two parts. From the Figure 2.11, we can see that the four windows on the right side of the UI are used to visualize a volume. The left side shows the SubjectHierarchyTreeView which the module already stored many data nodes. The first node is the DICOM patient data with the chest CT scans stored as a volume, and the cropped volume I generated with Crop Volume Module. There is a Volume rendering ROI node and several ScalarVolumeNode which are the generated segmentation volume with different parameters.

The left side is the module UI. This part is designed and implemented differently based on the requirements of the modules. The Figure 2.12 shows the module UI that the AGR implemented, where each parameter stored to be passing to the algorithm class.

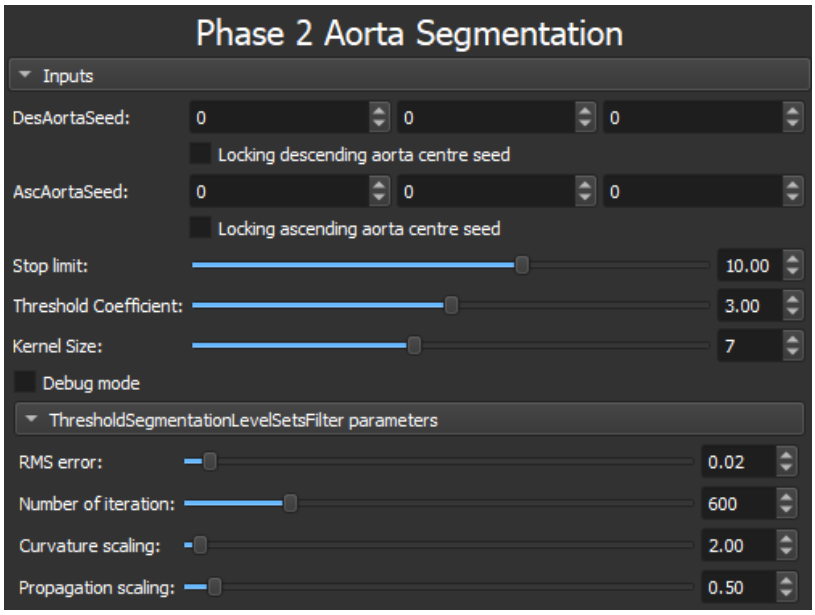



Figure 2.12: AortaGeomRecon Module UI

#### 2.3.3.2 Module's Workflow

When the user first starting 3D Slicer and click on the AGR module, this warning message and Tips appears in the module UI. The user must click on the confirm button below to proceed into the next steps. This warning message is an evidence for the assurance case, which I will explain in the next chapter.

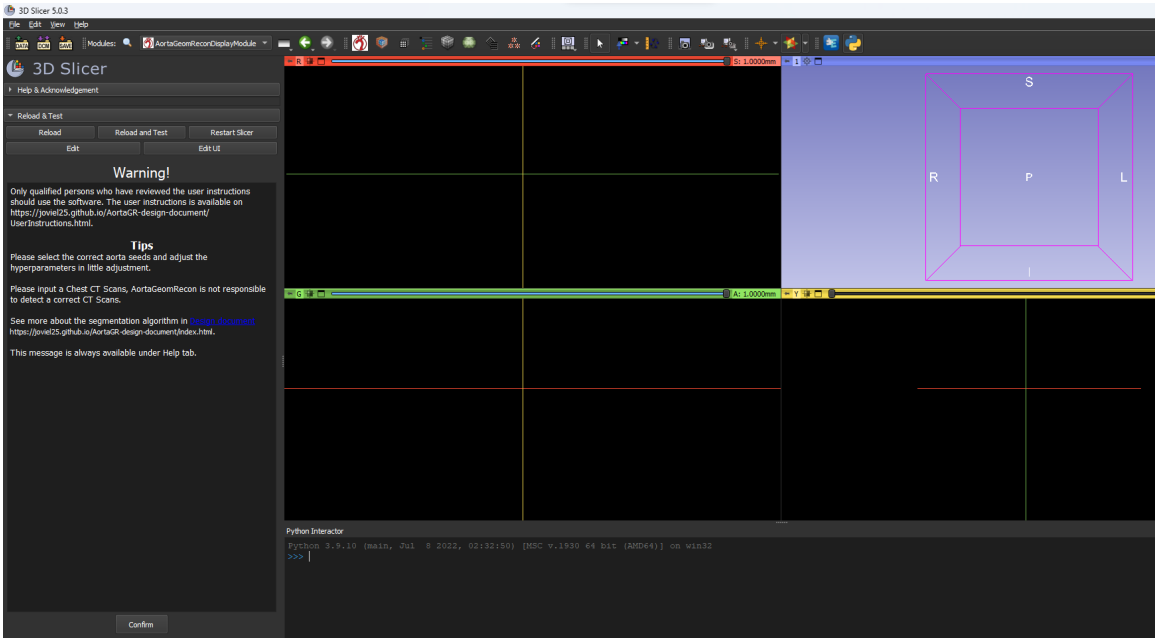



Figure 2.13: AortaGeomRecon Warning message

In the next step, assuming that the user has already read a DICOM image of the patient's chest, the user is asked to generate a cropped volume using the 3D Slicer's Volume Rendering module and the Crop Volume module. In this phase, the module UI displays only a SubjectHierarchyTreeView where the large data node are shown in this view. After generated a cropped volume, the apply button is enabled and the user can proceed to the next step.

In phase 2 aorta segmentation, the user is asked to input the parameters to perform

the segmentation. The module UI is same as the Figure 2.12. The necessary inputs are the two aorta seeds. Without any value for these two inputs, the module will not allow the user to generate a segmentation result. One of the advantages of using 3D Slicer is the interactive UI that supports reading coordinates on the volume interactively. On the right side of the Figure 2.11, we see a crossed intersection pointing to parts of the aorta, this intersection point allows the developer to read the coordinates. Moreover, we were able to automatically pick up the coordinates in real-time in the coordinate widget. As the user moving the intersection, we get the coordinate readings. The Figure 2.12 also demonstrates that the user can lock a seed, so the program stops picking up newest coordinate from the intersection point.

# Chapter 3

# Assurance Cases and Selected Evidence for AortaGeomRecon

In this chapter, I discuss the scope of our work, which is building the evidence to support each claim of our AC for AGR. The top level claims of the AC developed in previous work [18] is correct and complete, thus I have a list of evidence that can support the arguments and the top level claims. Our work focus on providing the correct evidence for the assurance case, and the following material is presented: the Software Requirements Specification of AGR, the Design Document, the Module Guide, the Test Plan, the Algorithm Review, the User Manual, the User Instruction Video, and a Warning Message implemented in AGR.

## 3.1 Assurance Case Development

Assurance Case is build with claims, subclaims, contexts and the evidence. The parts of the AC add up to an argument for why the top level claim is true. By using Astah

System Safety software to present the Goal Structuring Notation (GSN) arguments [2][10], I want to show that our software delivers correct outputs when used for its intended use/purpose in its intended environment, and within its assumed operating assumptions. The Figure 3.1 shows the top level of the assurance cases. With the goal of arguing that the software delivers correct outputs, I decompose the goal into 4 sub goals: GR, GI, GA and GBA, where GR stands for the goal of correct requirements of the software, GI stands for the goal of the implementation matching the requirements, GBA is the goal of that all operational assumptions have been defined, and GA is the goal that all operational assumptions are met.

## 3.2 Assurance Case for Software Specification Requirements

The first goal of getting a trusted software is having a complete, unambiguous, correct, consistent, verifiable, modifiable and traceable SRS that shows the complete breakdown of the requirements with mathematical notation, data models and instance models. The SRS is the foundation of the software development, and the design and the implementation will be based on the requirement document.

The Figure 3.2 demonstrates the claims on the goal of correct requirements of AGR. On the left branch, GR_3C implies the goal of a complete, correct, and consistent documentation. Under this claim, the goal is separated based on each characteristic, and the corresponding evidence is presented as the leaf node. The S_Correctness and S_Completeness.4 node require a domain expert to review the quality of the

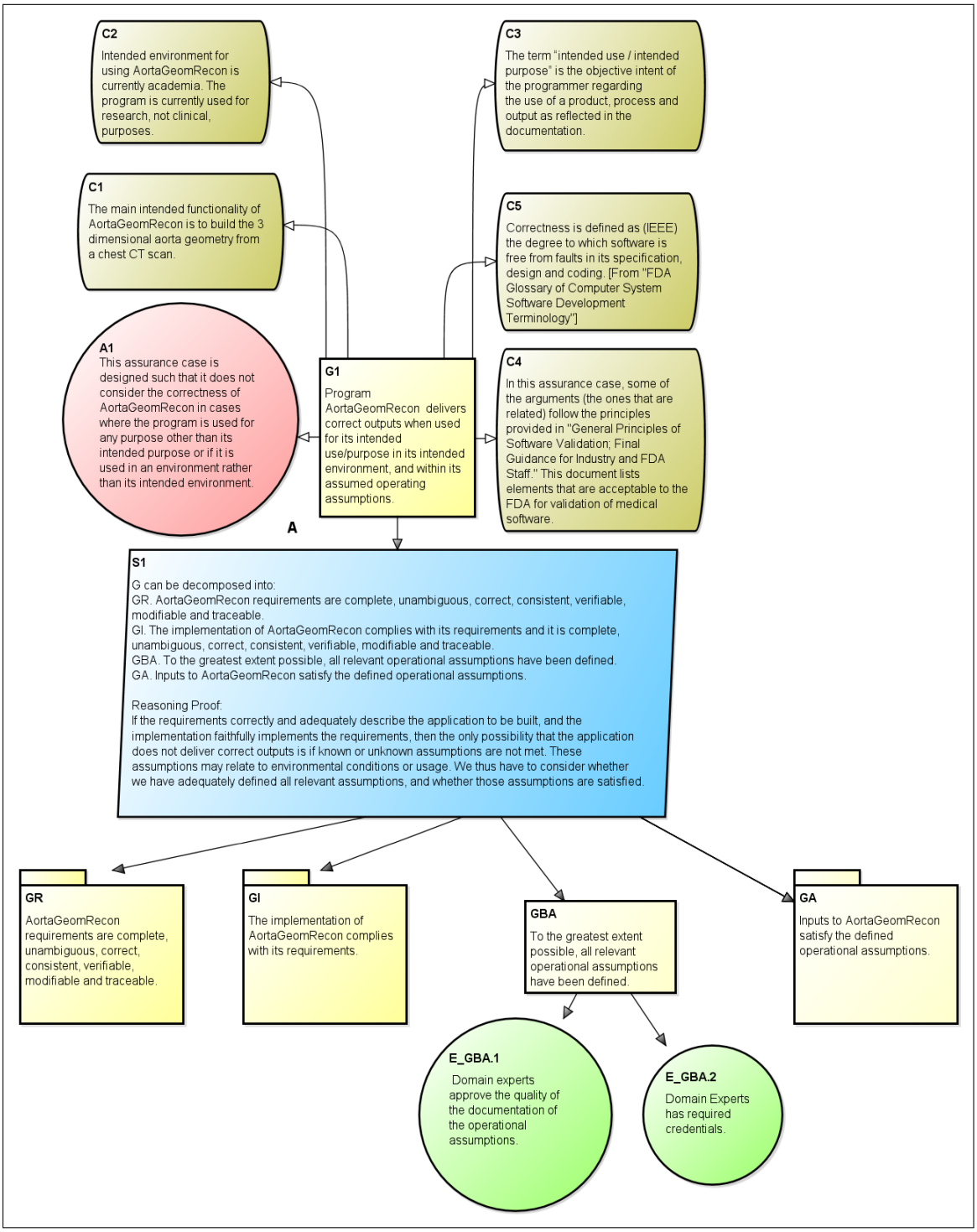



Figure 3.1: AGR Assurance Cases Top Level

document to ensure the documentation met the goal of the claims. The other characteristics of the documentation are supported with evidence as shown in the other branches in GR.

As explains in the assurance case GR, one of most important statement of SRS having these characteristics is using a standard template. This document is attached as Appendix A. Using a standard template means that all necessary requirements have been defined, and it allows a domain expert who has used this template to verify the quality of the document. I used a template tailored for research software [19], which is the standard template in the evidence E_Completeness.1, and all other evidences where a template is included.

### 3.2.1 The Chapters of SRS

The chapters in the SRS and some of the most important sections in the chapter are explained below:

- Reference Material

  In this section, a Table of Symbols and an Abbreviations and Acronyms table are used to explain every symbol and Abbreviations used in the SRS document. These tables ensure the consistency and the unambiguous characteristics of the document, as the evidences E_Consistency.1 and E_Unambiguous.1 shown in the Figure 3.2. They are located at the very beginning of the document, so the reader can first look at these tables before reading the entire document.

- Introduction

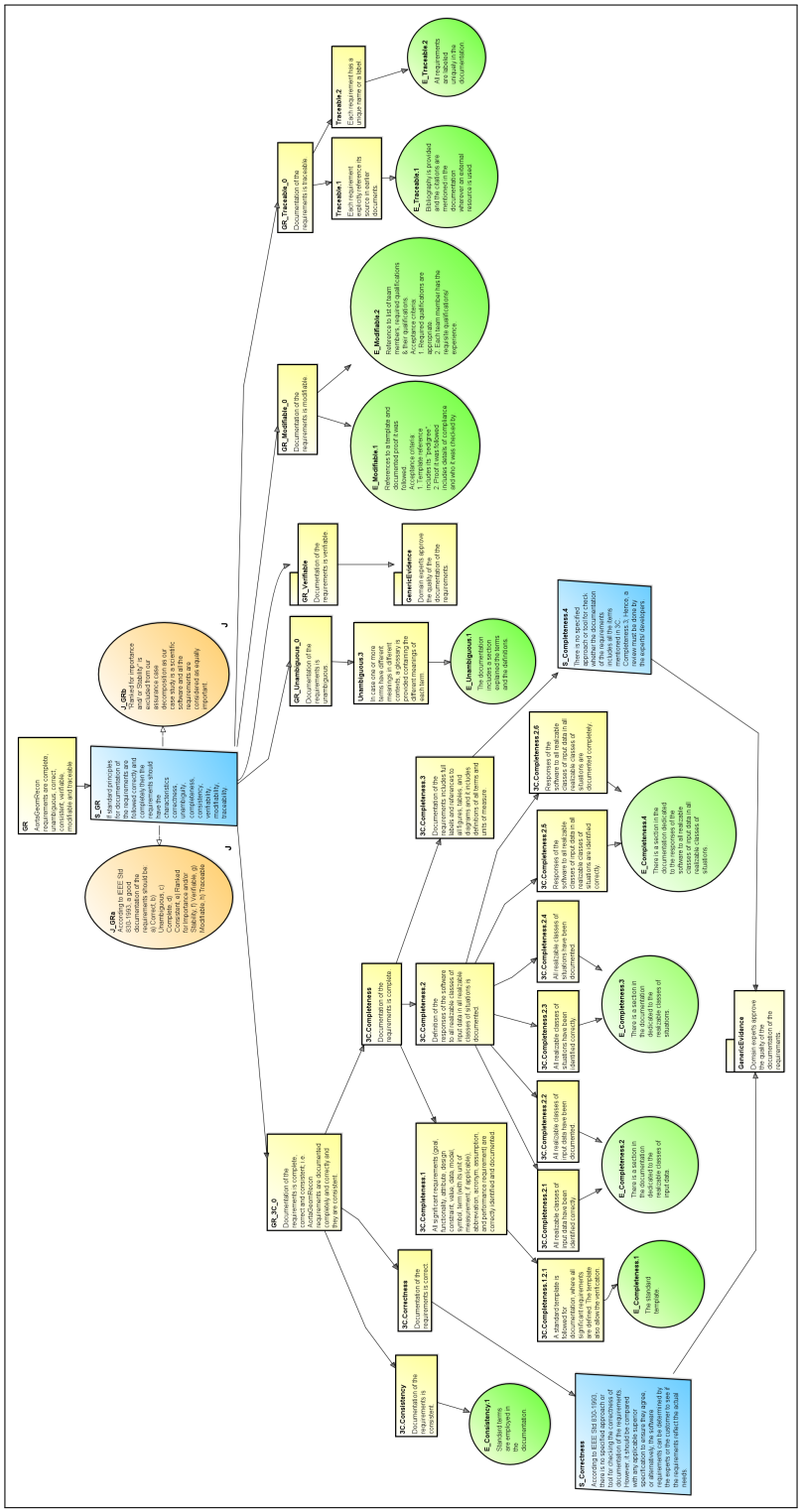



Figure 3.2: AGR Assurance Cases GR

In the introduction section, I introduced the problems and the scope of the document. These are subsections for explaining the purpose of document, abstracting the scope of requirements and defining the characteristics of the intended reader. This is provided for the reader to eliminates unambiguous in reading the document.

- General System Description

  The general system description includes a system context diagram which explains the relationship between the users, the inputs given by the user and the outputs of the AGR program. User responsibility and AGR responsibility are defined.

- Specific System Description

  In this section, I present more details about the problem and the specific system to solve the problem. The first subsection, Problem Description, discusses the definition of Organ Segmentation, the Coordinate Systems used in medical image problem, and Goal Statements. The goal for AGR is to extract the three-dimensional segmentation of the aorta.

  In the next subsection, Solution Characteristics Specification, I started with the assumptions, as shown in Figure3.3, to clearly define the scope of the requirement document, as shown in Figure 3.3. In the subsection Data Definitions, I defined Voxel, Image/Slice, and Volume with mathematical notation so that the developer can easily interpret, as shown in Figure 3.20. Next, in the subsection Instance Model, I showed the mathematical meaning of Region of Interest in Figure 3.5, and Segmentation in Figure 3.6, which are the two essential models

that the developer must know to develop the solution. The Data Definitions and Instance Model sections are the evidences E_Completeness.2, E_Completeness.3 and E_Completeness.4, which states that there is a section in the documentation dedicated to the realizable classes of input data, realizable classes of situation and the responss of the software to all realizable classes of input data in all realizable classes of situation. The Data Definition section defines the realizable classes of input data, the Instance Model section defines the realizable classes of situation and the response of the software.

## 4.2 Solution Characteristics Specification

### 4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [T], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

A1: The 3D image provided by the user must contain a visually distingushable aorta volume [IM1].

A2: User should select a valid region of interest [IM2].

A3: User should input a singular volume (3 dimensional image) even if the data format supports the 4th dimension (time) [IM1].

Figure 3.3: AGR SRS Assumptions

| Number | DD1 |
|---|---|
| Label | **Voxel** |
| Symbol | $v : \mathbb{R}$ |
| SI Units | - |
| Equation | - |
| Description | A slice (DD2) consists of $n \times n$ voxels. A real number is assigned to each voxel to reports the intensity on a grey-scale image. |
| Sources | Nejad (2017) |
| Ref. By | DD2 |

| Number | DD2 |
|---|---|
| Label | **Image/Slice** |
| Symbol | $slice : \mathbb{R}^{m \times n}$ |
| SI Units | - |
| Equation | - |
| Description | A visual representation that is using only two spatial dimensions with a sequence of arrays where a voxel (DD1) represents the color or intensity. Each move in the transverse plane (Figure 4) is considered as one slice |
| Sources | Nejad (2017) |
| Ref. By | DD3 |

| Number | DD3 |
|---|---|
| Label | **Volume** |
| Symbol | $V : \mathbb{R}^{m \times n \times p}$ |
| SI Units | - |
| Equation | - |
| Description | A three-dimensional image is a sequence of some images/slices (DD2). |
| Sources | - |
| Ref. By | IM1 |

Figure 3.4: AGR SRS Data Definitions

The goals GS1 are solved by finding IM1 and perform IM2 on the aorta.

| Number | IM1 |
|---|---|
| Label | **Region of interest** |
| Inputs | $V_{\text{in}} : \mathbb{R}^{m_i \times n_i \times p_i}$ , $Start : \mathbb{N}^3$, $m_o, n_o, p_o : \mathbb{N}$, with the following constraints: $$0 \leq Start[0] < (m_i - 1)$$ $$0 \leq Start[1] < (n_i - 1)$$ $$0 \leq Start[2] < (p_i - 1)$$ $$0 < m_o \leq (m_i - Start[0])$$ $$0 < n_o \leq (n_i - Start[1])$$ $$0 < p_o \leq (p_i - Start[2])$$ |
| Output | $V_{\text{out}} : \mathbb{R}^{m_o \times n_o \times p_o}$ such that $$\forall(i, j, k : \mathbb{N} \mid$$ $$i \in [Start[0]..Start[0] + m_o] \wedge$$ $$j \in [Start[1]..Start[1] + n_o] \wedge$$ $$k \in [Start[2]..Start[2] + p_o] :$$ $$V_{\text{out}}[i][j][k] = V_{\text{in}}[i][j][k])$$ |
| Description | The regions of interest is a subset (shaped like a box) of the 3D $V_{\text{out}}$. This subset contains the anatomical structure that the users wants to read, process or extract. |
| Sources | |
| Ref. By | IM2 |

Figure 3.5: AGR SRS Instance Model Region Of Interest

| Number | IM2 |
|---|---|
| Label | **Segmentation** |
| Input | $V_{\text{in}} : \mathbb{R}^{m \times n \times p}$, $Seed\_a : \mathbb{N}^3$, $Seed\_d : \mathbb{N}^3$ |
| Output | $V_{\text{out}} : \mathbb{R}^{m \times n \times p}$ such that $$\begin{gathered}\forall (i, j, k : \mathbb{N} \mid \\ i \in [0..m-1] \wedge\ j \in [0..n-1] \wedge\ k \in [0..p-1] : \\ (V_{\text{in}}[i,j,k] \in \text{structure} \implies V_{\text{out}}[i,j,k] = HIGH \mid \\ V_{\text{in}}[i,j,k] \notin \text{structure} \implies V_{\text{out}}[i,j,k] = LOW))\end{gathered}$$ The inputs $Seed\_a$ and $Seed\_d$ are used to determine whether a given element of $V_{\text{in}}$ is in structure or not. |
| Description | The process of extract an anotomical structure from the original 3D volume. The extracted anotomical structure is represented with high intensity pixel value. The rest of the image should have a lower intensity pixel value. The segmentation needs the region of interset from IM1 to process less noise data. A seed is what the algorithm needed as the inputs to perform segmentation, the type of seed is different among different algorithm. The seeds in this section are the centre coordinate of the descending aorta and the ascending aorta. The yellow dots shown in Figure 5 are the example of the seed. |
| Sources | |
| Ref. By | R3, LC1 |

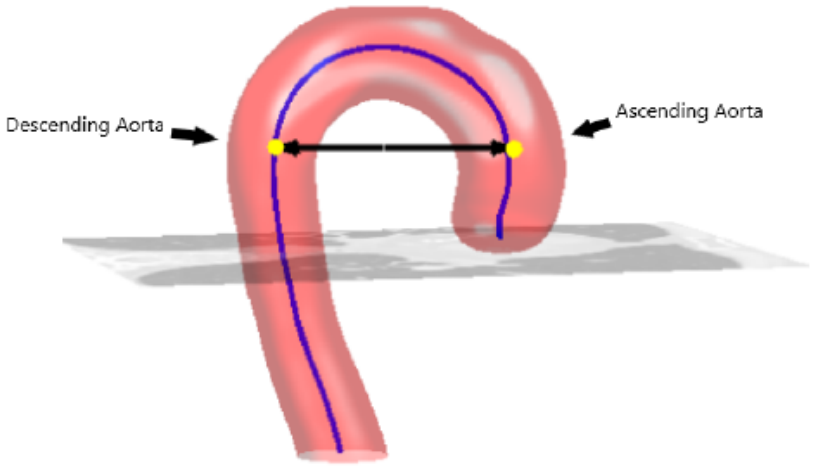



Figure 5: Aorta Seeds Kurugol et al. (2012)

Figure 3.6: AGR SRS Instance Model Region Of Interest

- Requirements

  With all the information in the document, I can now present the Functional Requirements and the Non-Functional Requirements for the program AGR. The Functional Requirements are defined by using the terms I presented in Data Definitions, Instance Model, and based on the other Functional Requirements, as shown in Figure 3.7. The Non-Functional Requirements usually have a measurement such as execution time, the effort of manual works. The Figure 3.8 demonstrates the Non-Functional Requirements, Usability, Safety, Learnability, Accurarcy and Consistency. The Functional Requirements and Non-Functional Requirements are labeled as the evidence E_Traceable.2 states.

**5.1 Functional Requirements**

R1: Input the following functions, data and parameters:

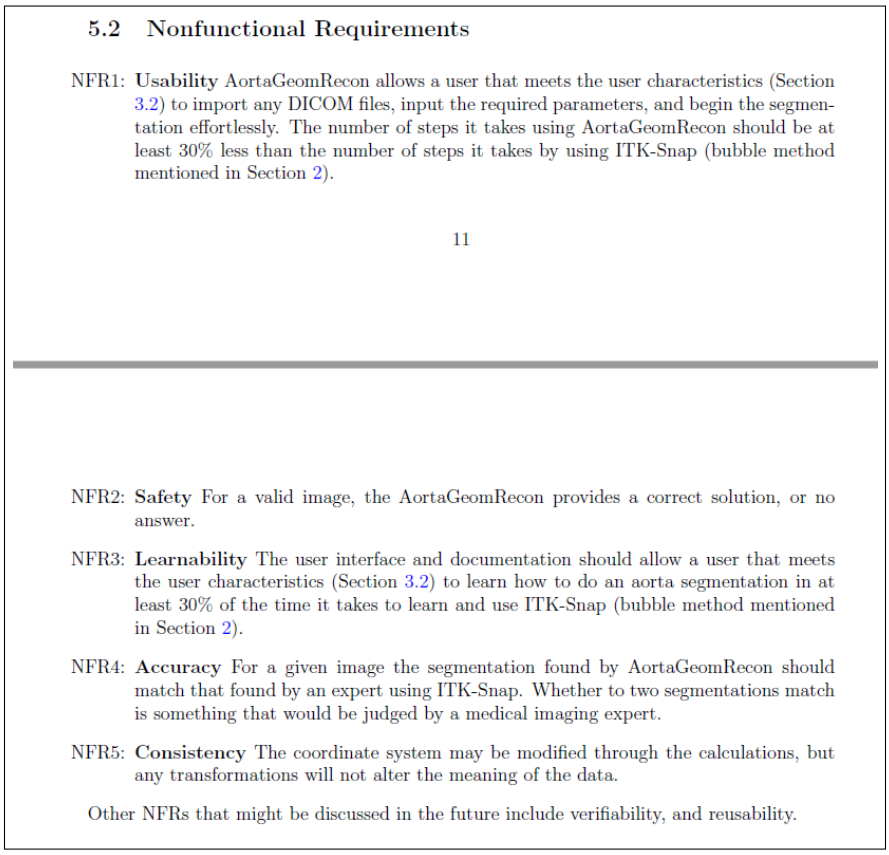
| symbol | description |
|---|---|
| $V$ | CT Scans volume (DD3) |
| $Seed\_a$ | The seed of ascending aorta centre coordinate (IM2) |
| $Seed\_d$ | The seed of descending aorta centre coordinate (IM2) |

R2: Use the volume in R1 to create a second volume, the region of interest (IM1) that contains all voxels of the aorta.

R3: Perform segmentation (IM2) on the volume created in R2.

R4: Visualize a volume (DD3).

Figure 3.7: AGR Functional Requirements



### 5.2 Nonfunctional Requirements

NFR1: **Usability** AortaGeomRecon allows a user that meets the user characteristics (Section 3.2) to import any DICOM files, input the required parameters, and begin the segmentation effortlessly. The number of steps it takes using AortaGeomRecon should be at least 30% less than the number of steps it takes by using ITK-Snap (bubble method mentioned in Section 2).

11

NFR2: **Safety** For a valid image, the AortaGeomRecon provides a correct solution, or no answer.

NFR3: **Learnability** The user interface and documentation should allow a user that meets the user characteristics (Section 3.2) to learn how to do an aorta segmentation in at least 30% of the time it takes to learn and use ITK-Snap (bubble method mentioned in Section 2).

NFR4: **Accuracy** For a given image the segmentation found by AortaGeomRecon should match that found by an expert using ITK-Snap. Whether to two segmentations match is something that would be judged by a medical imaging expert.

NFR5: **Consistency** The coordinate system may be modified through the calculations, but any transformations will not alter the meaning of the data.

Other NFRs that might be discussed in the future include verifiability, and reusability.

Figure 3.8: AGR Non- Functional Requirements

- Likely Changes and Unlikely Changes

  This section discussed the likely changes that the developer might expect a change in the future works, and the unlikely changes that is are not going to change for a justified reason. The only likely change discussed in the AGR's SRS is regarding the segmentation method. For different segmentation method, the inputs varies, since the segmentation method is a likely change, the inputs variables are also likely changes. The only unlikely change is the method of retrieving a region of interest. Most methods take a starting point and sizes in different dimensions to get the region of interest.

- Traceability Matrix and Graphs

  The traceability matrices are to provide easy references on what has to be additionally modified if a certain component is changed. Below shows the traceability matrices of different sections. The Figure 3.9 is the traceability matrix of the Data Definitions and Instance Models. The Figure 3.10 shows the relationship between the requirements and other sections. The Figure 3.11 shows the relationship between the assumptions and other sections.

| | DD1 | DD2 | DD3 | IM1 | IM2 |
|---|---|---|---|---|---|
| DD1 | | | | | |
| DD2 | X | | | | |
| DD3 | | X | | | |
| IM1 | | | X | | |
| IM2 | | | | X | |

Table 2: Traceability Matrix Showing the Connections Between Items of Different Sections

Figure 3.9: AGR Traceability Matrix between Data Definitions and Instance Model

| | IM1 | IM2 | R1 | R2 | R3 | R4 | NFR1 | NFR2 | NFR3 | NFR4 | NFR5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| IM1 | | | | X | | | | | | | |
| IM2 | | | | | X | | | | | | |
| R1 | | X | | | | | | | | | |
| R2 | X | | | | | | | | | | |
| R3 | | X | | | | | | | | | |
| R4 | | | | | | | X | | | | |
| NFR1 | | | X | X | X | X | | | X | | |
| NFR2 | | X | | | | | | | | | |
| NFR3 | | | | X | X | X | X | | | | |
| NFR4 | | X | | | | | | | | | |
| NFR5 | | X | | | | | | | | | |

Table 3: Traceability Matrix Showing the Connections Between Requirements and Instance Models

Figure 3.10: AGR Traceability Matrix Between Requirements and Other sections

| | A1 | A2 | A3 |
|---|---|---|---|
| DD1 | | | |
| DD2 | | | |
| DD3 | | | X |
| IM1 | X | | X |
| IM2 | | X | X |
| LC1 | X | X | X |
| UC1 | | | X |

Table 4: Traceability Matrix Showing the Connections Between Assumptions and Other Items

Figure 3.11: AGR Traceability Matrix Between Assumptions and Other sections

- Bibliography A Bibliography is provided at the end of SRS documentation, where it points to the template [19] that I use to write this documentation, and a list of citations whenever an external resource is used. This is related to the evidences E_Traceable.1, which states that a Bibliography is provided to include the citations of the external resource. The template is also related to E_Modifiable.1, which states that the documentation references to a template and documented proof it was followed.

### 3.2.2 Documentation Review

Documentation Review is necessary to ensure the documentation's correctness and completeness. When there is an update in the documentation, I used GitHub Issues and post a documentation review request as shown in Figure 3.12 to Dr. Spencer Smith, who has the requisite qualifications/experience to review the completeness and the correctness of the documentation. Additionally, the goal of the documentation being verifiable is also reviewed by Dr. Spencer Smith, and he approves the qualify of the documentation with the characteristic.

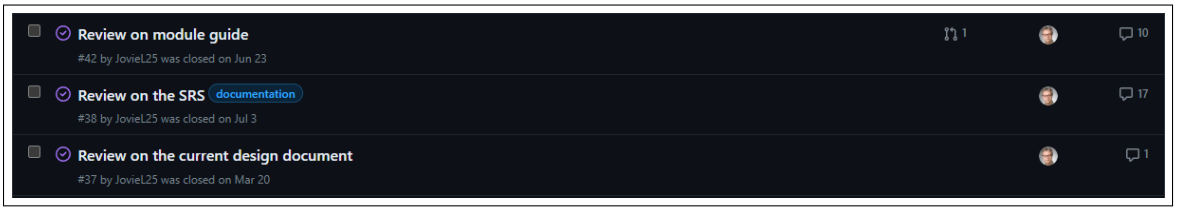



Figure 3.12: GitHub Repo Documentation Review Requests

## 3.3 Assurance Case for the Implementation

The goal of implementation is that it fully complies with the SRS. As Figure 3.13 shows, I argue this in two ways:

1. I argue that the implementation of the requirements has been verified.

2. I argue the design matches the requirement and that the implementation implies with the design, which implies that the implementation together matches the requirement.

In this section, I will focus on matching the developed artifacts to the evidence shown in Figure 3.13. In the first sub-section I will discuss the test plan of the AGR, particularly on how I build the continuous integration test infrastructure, test cases and provide a test procedure to test all requirements of the software. Next, I will show my design documents, including the Module Guide to demonstrate system architecture, and a design document for detailed design explanation. Finally, I will talk about the Code Walkthrough and the Algorithm Review, which helped us to eliminates bugs, errors, and increase our confidence in the implementation's completeness, and correctness.

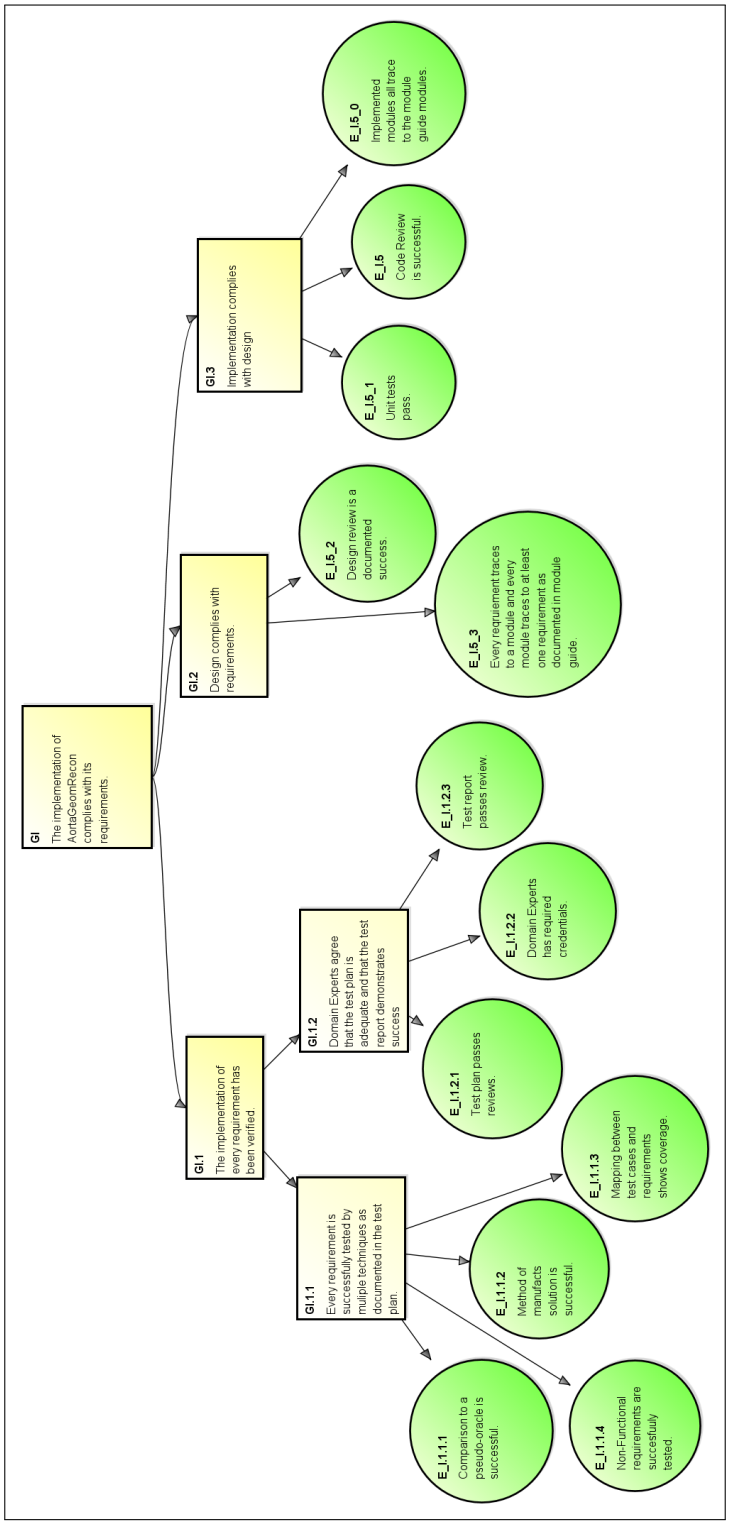



Figure 3.13: AGR Assurance Cases For Implementation

### 3.3.1 Test Plan

GI.1 states the goal of the implementaion of every requirement has been verified, so I need a test plan that is approved by a Domain Expert who has required credentials, and the tests cases covers all of the Functional Requirement and Non-Functional Requirements. Unlike the other algorithm that can easily be tested with a ground truth test case, our ground truth case is build by using another more accurate method such as ITK-Snap's bubble method, then manually crosing the unwanted pixels.

In this section, I will discuss on how I build a "Ground Truth" data with a verified version of the algorithm, then compare it with the result generated from the new updated version of the algorithm using Dice Similarity. Next, I will show how I use GitHub Actions workflow as the continuous integration infruscturue perform static code analysis and continuous integration tests. Then, I provide a test procedure to cover the Functional Requirements and Non-Functional Requirements, as the evidences under GI.1 state in Figure 3.13. Finally, I discuss on the test plan approval and the test report to includes the artifacts related to the evidences under GI.1.2.

#### 3.3.1.1 Build "Ground Truth" data

Since learning on how to build a true "Ground Truth" test case by using ITK-Snap is out of the scope of our project, I continuously build the "Ground Truth" test case with a previously verified version of the algorithm and a set of tuned hyperparameters. The only method to know which test case would be better is to have a manual review on the generated test case by a domain expert. The process of building the test case data is descibed as follow:

1. Generate a test case data with the previous satisfied version of the algorithm.

2. Generate a test case data with the new version of the algorithm.

3. Calculate the Dice similarity coefficient (DSC) of the two test case data.

4. If there is a strong difference in the DSC value, use visualization tool such as 3D Slicer to see the actual difference, and decide which test case to keep for the future.

The Dice similarity coefficient (DSC) was used as a statistical validation metric to evaluate the performance of both the reproducibility of manual segmentations and the spatial overlap accuracy of automated probabilistic fractional segmentation of MR images [24]. With a small DSC value, the evidence E_1.1.1 is achieved by comparing a new generated result with a pseudo-oracle. The statement of the evidence E_1.1.2 is also correct, which implied that a chosen approach or methodology has led to the creation of software that functions as intended, meets user requirements, and adheres to quality standards.

#### 3.3.1.2 GitHub Actions workflows

This leads to our Continuous Integration infrastructure, implemented with GitHub Actions workflow. A workflow is a configurable and automated process that will run one or more jobs on the desired system. GitHub Actions workflow used a YAML file to define the events and the commands to be executed on the temporary system, which has the build of the repository [8].

I have set up two automated process which happens on each "push" event and "pull" event. A "push" event implies that something is changed in one or multiple commits, therefore there is a need to verify whether the commits have bugs that need

extra fixes. A "pull" event happens when a feature branch is going to merge with the main branch. Since our main branch is protected, any update to the main branch must be merged by using a pull-request. Before a pull-request can be approved, the continuous integration tests are examined and until there are no errors, a pull-request cannot be merged with the main branch.

The first automated process is a linter. A linter is a tool for static code analysis to flag programming errors, bugs, stylistic errors and suspicious constructs. I used Python Flake8 as our linter to find bugs and errors, and ensures that program's readability by striking the source code with Google's published Python Style Guide. [22]

The second automated process is our continuous integration tests. By setting up Git Large File System (LFS) and upload to pre-build ground truth test data in the repository, I can now pass the cropped volume as the input data, the same aorta seeds and the hyperparameters that I have used to generate the ground truth test data to the algorithm and verify the results. By calculating the DSC value of both images, I can now set a limit such that the update to the algorithm is passing or failing our test if the DSC value is within the limit. This indicates that our evidence E_I.5_1 is accomplished.

#### 3.3.1.3 Test Procedure

In this section, I will introduce our test procedure for Functional Requirements and Non-Functional Requirements.

The Functional Requirements can be tested by generating a segmentation result from scratch in 3D Slicer. Without loading a MRMLscene file on purpose, 3D Slicer

is in its default state. The test procedure for testing the Functional Requirements is described as follow:

1. Open 3D Slicer.
2. Load a DICOM file using 3D Slicer's DICOM database.
3. Generate a ROI object using 3D Slicer's Volume Rendering module, as described in user manual.
4. Generate a cropped volume using 3D Slicer's Crop Volume module, as described in user manual.
5. Load AortaGeomReconDisplayModule, click on the "Apply" button to proceed to next step.
6. Input the aorta seeds.
7. Input the hyperparameters.
8. Click on the "Apply" button.
9. Visualize the segmentation result.

If step 1-4 did not proceed correctly, there is an error with 3D Slicer, which is out of the scope of the project. If an error happens in step 5-7, there might be an error with the plugin as a scripted module. Otherwise, step 8 generates a result is only concerns with the hyperparameters and the algorithm's implementation, and step 9 is affected by 3D Slicer and the result generated from step 8. This test procedure has all Functional Requirements match to a step, where R1 matches to step 2, R2

matches to step 3, R3 matches to step 8, and R4 matches to step 9. Thus, I have our evidence E_1.1.3.

The Non-Functional Requirements is difficult to test, because each user with different experience could result in different learning time, and total time it takes from scratch to generating a segmentation result. The test procedure used in Functional Requirement test can be used for Non-Functional Requirements test. Both NFR1 Usability and NFR3 Learability requires a measurement in time comparing to another software. NFR2 Safety, NFR4 Accuracy, and NFR5 Consitency requires a verification in the segmentation result. NFR4 Accuracy also requires a segmentation result generated by ITK-Snap. By performing all of the above action, I have all Non-Functional Requirements tested, which is the evidence E_1.1.4.

#### 3.3.1.4 Test Plan Approval and Test Report

GI.1.2 states that a domain expert with required credentials must review the test plan, and the test report. The test plan is reviewed by Dr. Spencer Smith, and our test report is partially automatically generated by GitHub Actions workflows, as shown in the Figure 3.14.

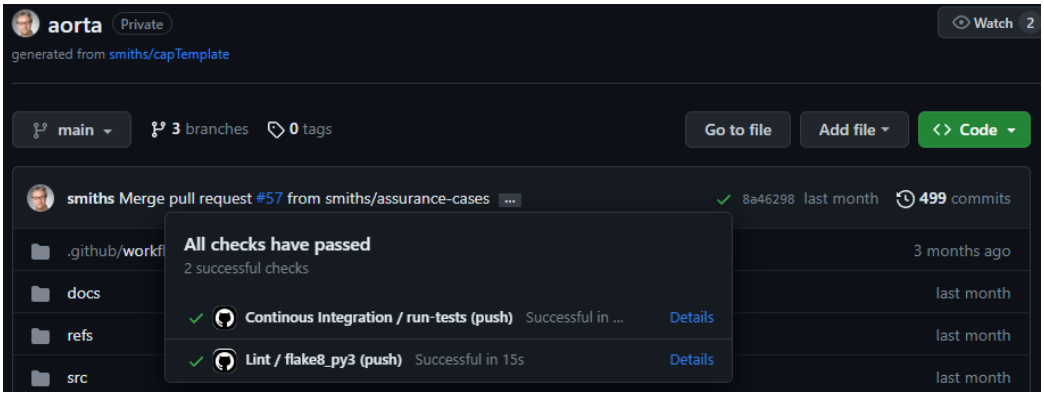



Figure 3.14: AGR Test Report

The GitHub will send an email to all the contributors when some checks were not successful, thus I are awared of these errors.

## 3.4 The Design Documentation of the AortaGeomRecon

In this section, we will discuss the design documents of the AortaGeomRecon. There are multiple aspects of the design document to discuss:

1. System architecture, or high levels design.
2. Detailed design explaning how the algorithm works.

The first item is presented with a Module Guide, and the second item is presented with a source code documentation generator, which generates the binary in HTML and is hosted on a web server.

### 3.4.1 Module Guide

An important document to show that the design is complete, correct, and consistent design is Module Guide (MG), which is attached as Appendix B. As explained previously, MG demonstrates the system architecture, or the high level design of the AortaGeomRecon. The designer typically keeps these anticipated changes isolated to a single module so if the change happens, only one module is impacted. The anticipated changes are listed in the Figure 3.15 below.

**AC1:** The specific hardware on which the software is running.

**AC2:** The format of the initial input data.

**AC3:** The algorithm to segment the aorta.

**AC4:** The data structures to store the input parameters required to execute the algorithm.

**AC5:** The methods to create a user interface.

**AC6:** The methods to retrieve a region of interest.

**AC7:** The methods to visualize a volume.

**AC8:** How the overall control of the calculations is orchestrated.

**AC9:** The format of the final output data.

Figure 3.15: AGR Anticipated Changes

Modules are decomposed according to the principle of "information hiding" proposed by Parnas et al. (1984). The Secrets' field in a module decomposition is a brief statement of the design decision hidden by the module. The Services' field specifies what the module will do without documenting how to do it. The module hierarchy and a part of the module decomposition is demonstrated in Figure 3.16 and Figure 3.17. For each module, a suggestion for the implementing software is given under the Implemented By title. If the entry is OS, this means that the module is provided by the operating system or by standard programming language libraries. AGR means the module will be implemented by the AGR software.

## 5 Module Hierarchy

This section provides an overview of the module design. Modules are summarized in a hierarchy decomposed by secrets in Table 1. The modules listed below, which are leaves in the hierarchy tree, are the modules that will actually be implemented.

**M1:** Hardware-Hiding Module

**M2:** Input Format Module

**M3:** Input Parameter Module

**M4:** Control Module

**M5:** GUI Module

**M6:** Volume Visualization Module

**M7:** Crop Volume Module

**M8:** Aorta Segmentation Module

**M9:** Image Processing Module

**M10:** Multidimensional Array Processing Module

**M11:** Digital Enhancement Module

Figure 3.16: AGR Modules

#### 7.2.2 Input Parameter Module (M3)

**Secrets:** The data structure for input parameters, how the values are input and how the values are verified. The load and verify secrets are isolated to their own access programs.

**Services:** Gets input from user, stores input and verifies that the input parameters comply with physical and software constraints. Throws an error if a parameter violates a physical constraint. Throws a warning if a parameter violates a software constraint. Stored parameters can be read individually, but write access is only to redefine the entire set of inputs.

**Implemented By:** AortaGeomRecon

**Source:** AortaSegmenter class' atributes

#### 7.2.3 Control Module (M4)

**Secrets:** The algorithm for coordinating the running of the program.

**Services:** Provides the main program's entry point, the ability to jump from a program state to another.

**Implemented By:** AortaGeomRecon

**Source:** AortaGeomReconDisplayModuleWidget module

#### 7.2.4 Volume Visualization Module (M6)

**Secrets:** The methods which allow users to visualize a 3D Volume.

**Services:** Display the aorta images and vtk 3D geometry.

**Implemented By:** 3D Slicer

Figure 3.17: AGR Module Decomposition Example

Now that I have listed the anticipated changes and the modules, I use traceability matrices to show the relationships between the modules and the anticipated changes, and between the modules and the requirements, as shown in Figure 3.18. This indicates that the design is fully complying with the requirements, as I stated in the evidence E_I.5_3, under the GI.2 in the Figure 3.13.

| Req. | Modules |
|---|---|
| R1 | M1, M2, M3, M4 |
| R2 | M3, M7 |
| R3 | M8, M9, M10 |
| R4 | M6 |
| NFR1 | M3, M4, M5 |
| NFR2 | M4, M8, M9, M10 |
| NFR3 | M3, M4, M5 M6, M7, M8 |
| NFR4 | M7, M8, M9, M10 |
| NFR5 | M3 |

Table 2: Trace Between Requirements and Modules

| AC | Modules |
|---|---|
| AC1 | M1 |
| AC2 | M2 |
| AC3 | M8 |
| AC4 | M3 |
| AC5 | M5 |
| AC6 | M7 |
| AC7 | M6 |
| AC8 | M4 |
| AC9 | M9, M10 |

Table 3: Trace Between Anticipated Changes and Modules

Figure 3.18: AGR Modules Traceability Matrices

On top of relating the modules to the requirements, I am relating the actual source code to the modules, which is a strong evidence of our implementation complies with the requirements, as shown in Figure 3.19. Module 11 Digital Enhancement Module is an example of Module mapping to a piece of the source code. In the comments on top, I added the source file where this piece of the source code is located, as well as the exact places with GitHub and the exact lines highlighed. This table demonstrates that the implemented modules all traces to the module guide modules, as stated in the evidence E_I.5_0.

| | |
|---|---|
| M6 Volume Visualization Module | 3D Slicer's Volume Rendering Module<br>3D Slicer's Volume Rendering Source Code |
| M7 Crop Volume Module | 3D Slicer's Crop Volume Module<br>3D Slicer's Crop Volume Module Source Code |
| M8 Aorta Segmentation Module | AortaSegmenter class |
| M9 Image Processing Module | SimpleITK |
| M10 Multi-Dimensional Array Processing Module | NumPy |
| M11 Digital Enhancement Module | |

```
# AortaGeomReconDisplayModule.py
# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModule.py#L739-L769
    def transform_image(self, cropped_volume):
        """
        Histogram Equalization for Digital Image Enhancement.
        https://levelup.gitconnected.com/introduction-to-histogram-
            equalization-for-digital-image-enhancement-420696db9e43
        """
        cropped_image = sitkUtils.PullVolumeFromSlicer(cropped_volume)
        img_array = sitk.GetArrayFromImage(
            (sitk.Cast(sitk.RescaleIntensity(cropped_image), sitk.
                sitkUInt8)))
        histogram_array = np.bincount(img_array.flatten(), minlength=256)
        num_pixels = np.sum(histogram_array)
        histogram_array = histogram_array/num_pixels
        chistogram_array = np.cumsum(histogram_array)
        transform_map = np.floor(255 * chistogram_array).astype(np.uint8)
        img_list = list(img_array.flatten())
        eq_img_list = [transform_map[p] for p in img_list]
        eq_img_array = np.reshape(np.asarray(eq_img_list), img_array.
            shape)
        eq_img = sitk.GetImageFromArray(eq_img_array)
        eq_img.CopyInformation(cropped_image)
        median = sitk.MedianImageFilter()
        median_img = sitk.Cast(median.Execute(eq_img), sitk.sitkUInt8)
        self._cropped_image = median_img
```

Table 4: Trace Between Modules and Code

Figure 3.19: AGR Part Of The Traceability Matrix On Modules And Code

### 3.4.2 Detailed Design Document

The purpose of the Design Document [14] is to explain in details how the algorithm works, and why it worked. Similar to what section 2.2.3 wrote, the design document explains in plain text the workflow of the algorithm. The design document is a piece of evidences that demonstrate unambiguity. Moreover, this document can let the domain expert to do a design review without reading the source codes directly, which helps building the evidence E_I.5_2.

To show and automate the detailed design, I used Sphinx, a Python Documentation Generator that can build module's documentation from the comments in the source code. Moreover, using reStructuredText to write the Algorithm Overview, I can build HTML code which can be published on a web server, as shown in Figure 3.20, which shows the index page of the website.

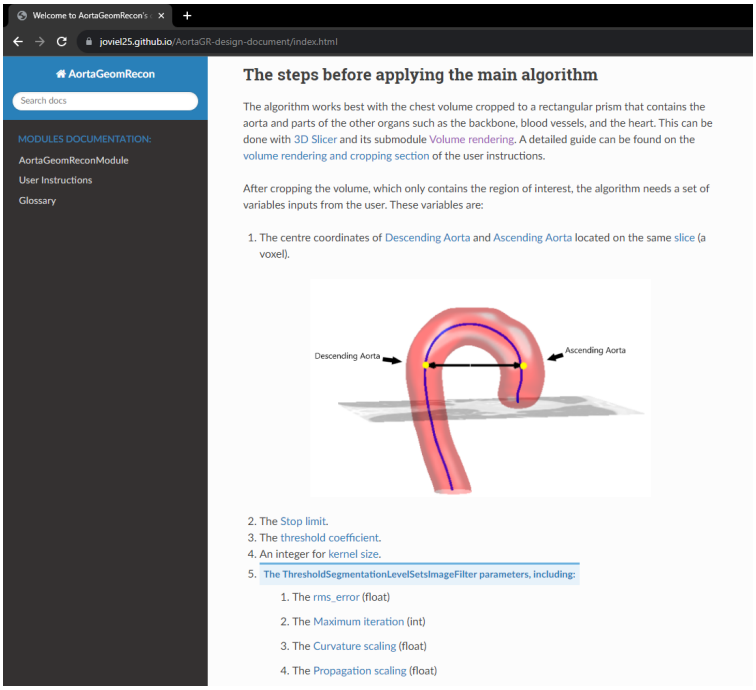



Figure 3.20: AGR Design Document Website

Another important section in detailed design document is the Glossary. It has a rich vocabulary explanation, images, and links to the outside source to let the reader understands as much as possible, as demonstrated in Figure 3.21.

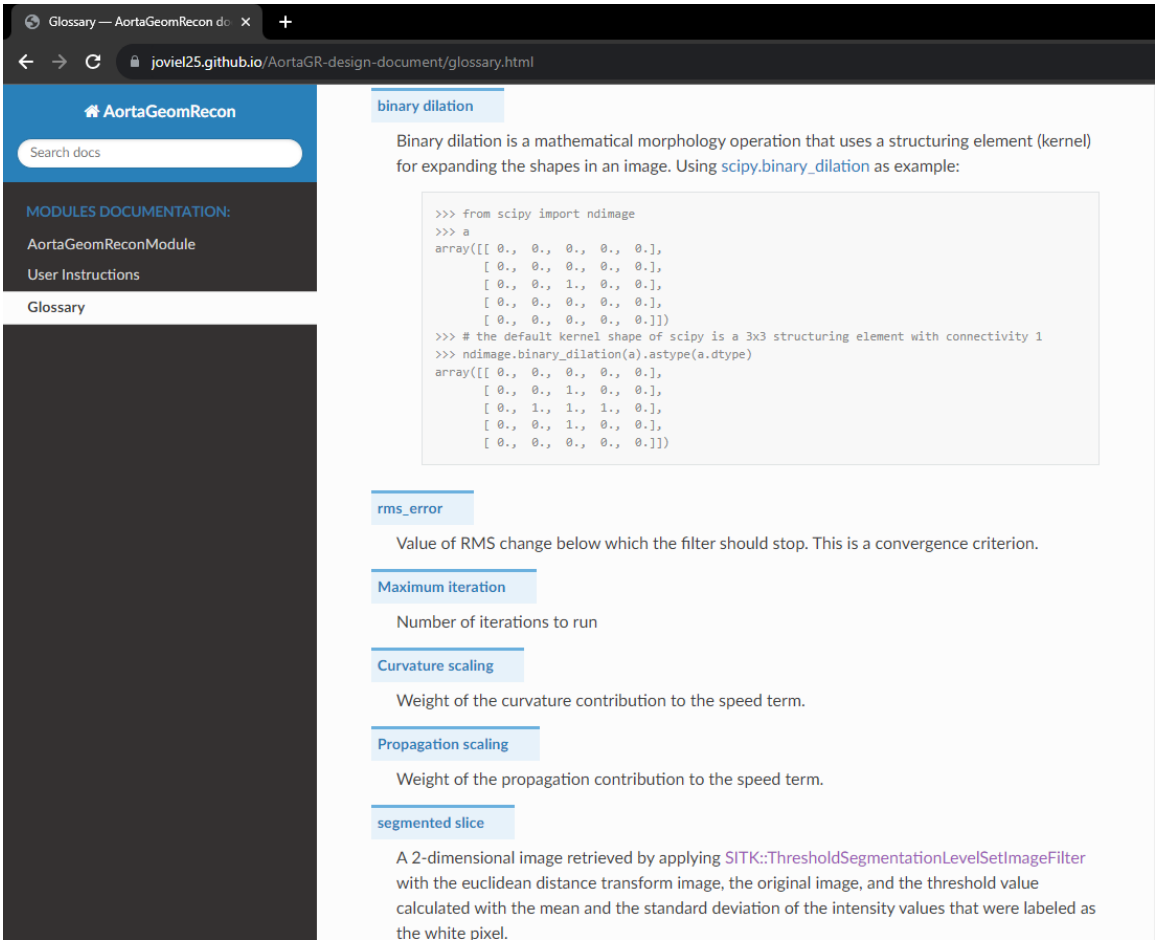



Figure 3.21: AGR Design Document Glossary

### 3.4.3 Algorithm Review

The Algorithm Review started with a Code Walkthrough. A Code Walkthrough is a systematic and collaborative process in software development where a team of developers, designers, and stakeholders review and analyze a piece of code, typically

with the aim of identifying defects, potential issues, and improvements [5]. During a Code Walkthrough, participants examine the code line by line, discussing its design, functionality, readability, maintainability, and adherence to coding standards. The process involves both the author of the code and other team members, fostering knowledge sharing and collective learning. The goal is to catch issues and enhance the codebase through collective expertise.

We contrast a Code Review with an Algorithm Review. In an Algorithm Review, we present the algorithm to the domain expert and asking them if the detailed design fulfill the implementation objectives. In a Code Review, we are inspecting the implementation and verifying if the implementation has followed the design.

In this section, I will discuss the Code Review with Kailin Chu, and the key takeaways from this meeting. Then, I will discuss the Algorithm Review with Dr. Dean Inglis, which the meeting has reinforced our confidence in the design. Finally, I will briefly introduce the tools that we have used in both meetings.

#### 3.4.3.1 Code Review with Kailin Chu

The Code Review was done with Kailin Chu, who is a biomedical engineering student and started working the semi-automacial aorta segmentation algorithm as a summer researcher. The meeting happened on Thursday, April 20, 2023, and the duration is about an hour. Along with Dr. Smith Spencer, I was aiming to increase our confidence in the code via a Code Walkthrough. This code walkthrough did not increase our confidence in the software and it became a Code Review, because the code was developed by Kailin from two years ago, so some details and design decisions were missing, and some variables were decided by trial and error. Despite that the code walkthrough

has turned into an algorithm review, and it did not achieve what I wanted in the first place, this meeting was still very helpful. Originally, the old method to generate a label image that we have discussed in the section 2.2.4.1 is partialy random when the algorithm is segmenting on the superior direction. This happened when from axial view going toward the head direction, we are observing that ascending aorta and the descending aorta is going to merge into one piece. However, the segmentation on the aortic arch requires the algorithm to generate a label image to cover part of the descending aorta. This coverage is sometime missing when executing on certain test case. Knowing that this part of the algorithm was partially based on trial and error, I was confident on improving the algorithm by using the idea of centroids. By using two centroids, one centroid on the ascending aorta and another on the descending aorta, the centroids can keep track of the most centered position of ascending aorta and descending aorta when the aortic arch region is reached. Thus, it generates a better label image, and it will generate a more accurate segmentation result.

#### 3.4.3.2 Algorithm Review with Dr. Dean Inglis

The algorithm review was conducted with Dr. Dean Inglis, an experienced professor, Medical Image Analyst, and Software Developer. The meeting happened on May 17, 2023, and the duration is about one and half hour. I presented our segmentation algorithm to him and requested validation of our approach or suggestions for a potentially superior algorithm. Dr. Dean Inglis provided his insights on the algorithm, which I meticulously recorded on the GitHub issue tracker. These insights will guide the developer responsible for enhancing the program. This meeting significantly reinforced our confidence in both the software and our endeavors, because the methods

discussed in the section 2.2.4.1, 2.2.4.2, and **??** were very common in image analysis. The level sets segmentation is also a often used technique for image segmentation. This indicates that the evidence E_I.5 is accomplished.

#### 3.4.3.3 Tool used in Algorithm Review

Spyder is a free and open source scientific environment written in Python, for Python, and designed by and for scientists, engineers and data analysts. The Variable Explorer allows the user to interactively browse the variables and the objects in debugging mode [17].


Figure 3.22: Spyder Variable Explorer [17]

This feature allows us to execute the program step by step, and see what happens to the variable (segmentation result) when executing the segmentation algorithm.

## 3.5 Assurance Case for Operational Assumptions

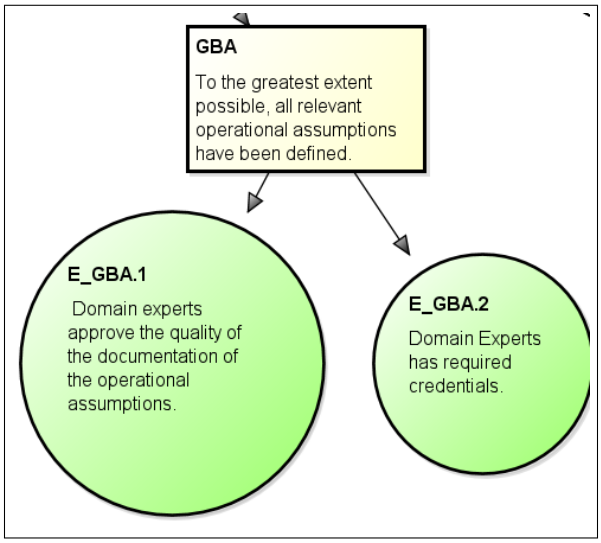



Figure 3.23: AGR Assurance Case Operational Assumptions

The evidence for the statement "To the greatest extent possible, all relevant operational assumptions have been defined" is quite simple as all that is required is a qualified Domain experts approve the quality of the documentation. However, finalizing this evidence takes significant effort from the beginning of the project to the end of the project, because I want to continuously improve the quality of the content matching the most recent updates of the software.

In this section, we will present two methods to define all relevant operational assumptions. The first method is a User Manual, which is written in plain text and multiple screenshots. The second method is a User Instructional Video, which includes voice over to guide the user step by step.

### 3.5.1 User Manual

A user manual serves the purpose of documenting all operational assumptions. When the user gets unexpected results by using this software, they should be able to refer to the user manual to see what pieces are different. Our user manual is initially located in GitHub repo's README, as shown in Figure 3.24, which is only available to the developers invited as the GitHub project contributors. The content includes the installation of the software, importing the extension modules, import inputs data, and perform segmentation. The user manual is also available publicly on the design document website, assuming that the users might not be the repository contributors.

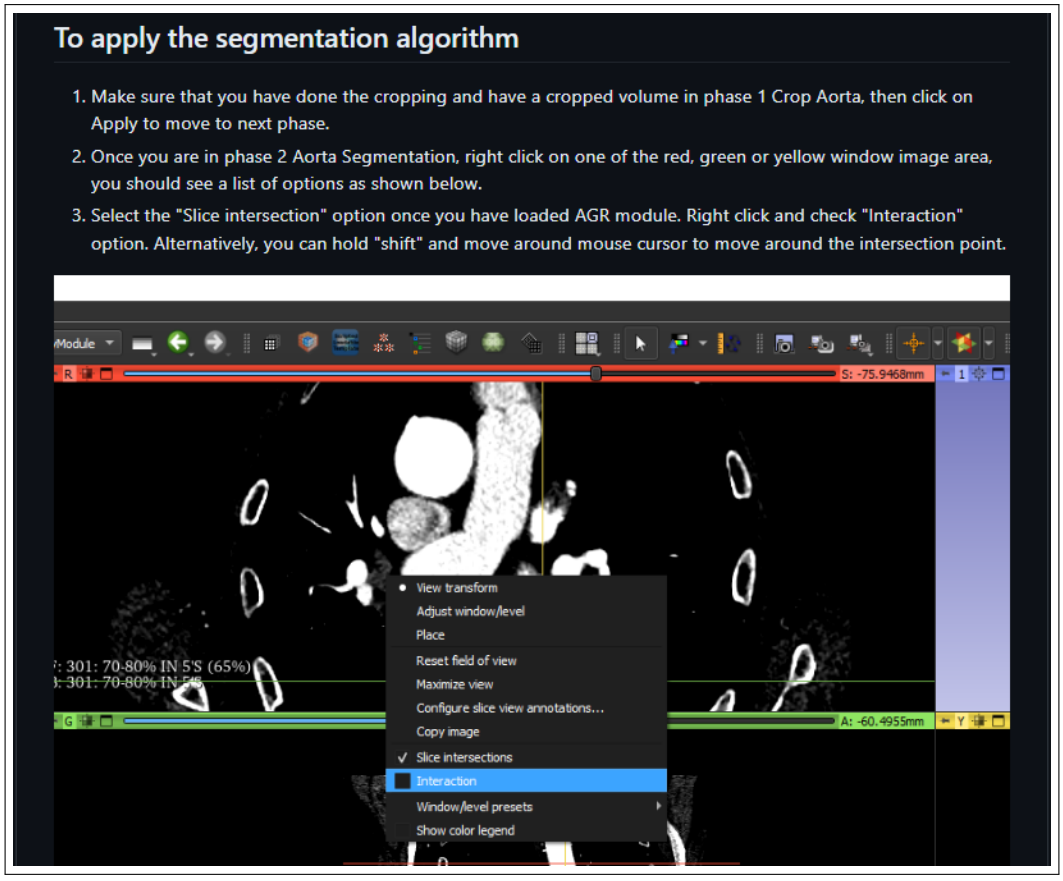



Figure 3.24: AGR User Manual On GitHub README

### 3.5.2 User Instruction Video

Videos are an effective way to engage your audience and deliver information in a way that's easy to follow along and understand. A better instructional content is a YouTube Video where I make step-by-step instruction with voice over to instruct user. The Figure 3.25 shows the playing video on YouTube. The video is not listed publicly on YouTube, but the users who have access to the GitHub repository or Design Document website can access this video by the URL link.

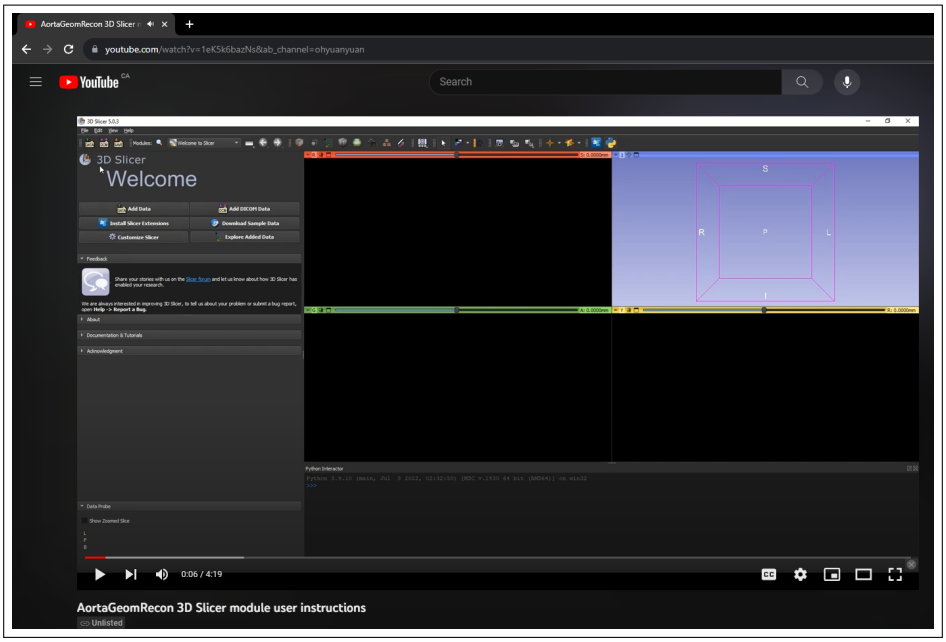



Figure 3.25: AGR User Instructions on YouTube

## 3.6 Assurance Case for Inputs Assumptions

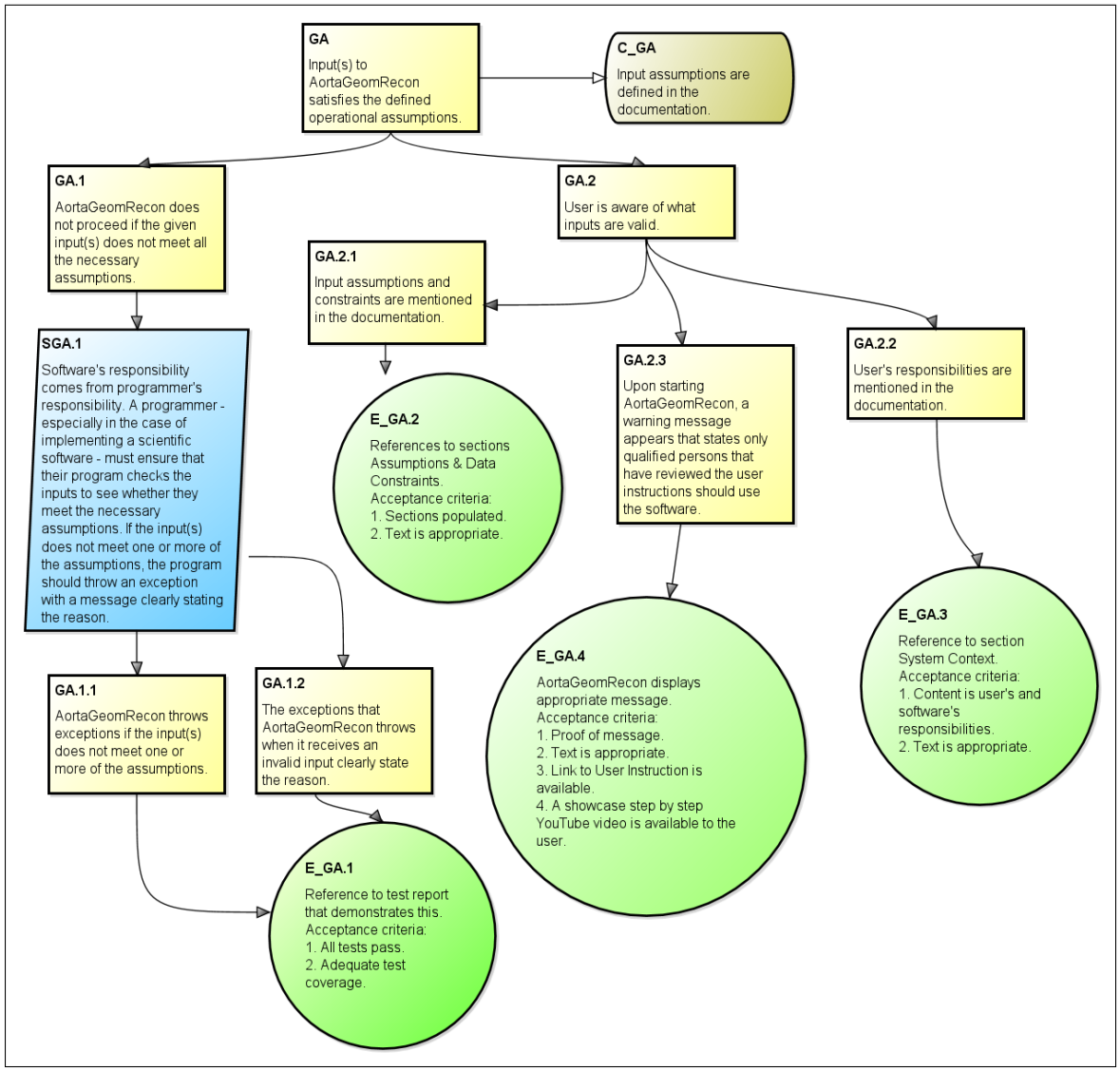



Figure 3.26: AGR Assurance Case Inputs Assumptions

The Figure 3.26 shows our last assurance case, GA. This statement requires the user know what inputs are valid, and only uses the valid inputs in the software. When the software gets unexpected inputs, it should not proceed to the next step, which could

result in unexpected outputs.

### 3.6.1 AortaGoemRecon's Control Sequence

In the logic of the control sequence implemented as the 3D Slicer scripted module, the appropriate inputs must meet the necessary assumptions before proceed into the next step. In phase one, a cropped volume with a name that includes the string "cropped" must be present in the node storage, where a cropped volume created by Crop Volume module will automatically named with the string "cropped" as part of the volume's name. Otherwise, the user cannot go to the next phase through normal operation. In phase two, the aorta seeds must be provided to continue to the segmentation. This implies that our evidence E_GA.1 is satisfied.

### 3.6.2 Warning Message

As I initially planned, the references to sections Assumptions, Data Constraints, and System Context is available in the User Manual and User Instruction Video, where I showed the user how to import DICOM patient's data, and operate on the inputs' data till I get a segmentation result. This implies that the requirements of the evidences E_GA.2, E_GA.3 and E_GA.4 are met. A user who has read the User Manual and watched the instruction video should know what inputs are valid. Therefore, in the AGR module, I need to effectively guide the user to the User Manual, whether the user has used this software before or is a first time user.

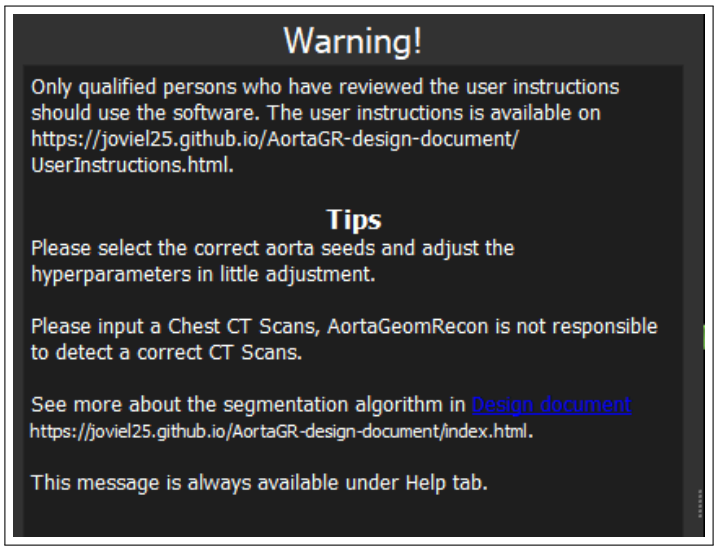



Figure 3.27: AGR Warning Message

As mentioned in the section 2.3.3.2, when the user first starts 3D Slicer and click on the AGR module, this warning message appears, which is also referred as the appropriate message stated in E_GA.4. The user must clicks on the Confirm button to continue to the next steps. With the warning message shown to the user, it is now the user's responsibility to use the valid inputs for AGR, which the program will deliver the correct outputs if the other operations are performed correctly.

# Chapter 4

# Conclusion and Future Works

In this chapter, we provide a summary of the thesis as well as the future work.

## 4.1 Thesis Summary

In this project, we developed a software as a 3D Slicer extension to semi-automatically extract the 3D geometry of the aorta, while applying assurance case arguments to build our confidence in this medical software. The project has started from a Jupyter Notebook program, then explored from the point of view of a patient such that what can we do to trust the software enough to let the doctor using it while being confident and certain that the software will not fail our expectation. We have then developed an idea of developing a software that is first conveniant to use, at least on gathering parameters. This lead to developing a 3D Slicer extension module, because 3D Slicer already provides useful features such as Volume Rendering, Volume visualization, Crop Volume, etc. While building the software, we build the assurance cases in Goal Structuring Notation with the bottom-up approaches; we keep ask ourself what are

the evidences that are necessary to support our claim in requirements, implementation, operational assumptions and inputs assumptions? Keep that question in mind, we have finalized our SRS document, Module Guide document, wrote user instructions, built design document in HTML and publish it on a website, and linking all assurance cases to support our arguments. Finally, we have used GitHub's features for Continuous Integration infrastructure, and project management. We have built 2 automated process that act as a linter and continuous integration tests, these processes helped a lot in detecting bugs and errors in implementation. As for project management, GitHub Issues, Discussions, and Pull requests were used throughout the development of the software. Me and Dr. Spencer Smith were able to keep up good communication through these features.

In the course of this project, we have summarized a list of challenges and tasks that we could have done better. The first challenge was looking for an ideal platform to develop AortaGeomRecon software. Until the point where we see that it is nearly impossible to build from scratch a volume visualization system like the volume visualization provided by 3D Slicer, time and efforts have been wasted in design a UI, finding the right tool to build the UI, etc. 3D Slicer itself is a very complex software, the development resource is limited and difficult to understand.

Another obstacle that we have is having a domain expert to examine the quality of our segmentation result and other documentation. This medical software's intended user is a university student studying in medical science or medicine, who likes to get an aorta's image or quantified volume. Throughout the development of the AortaGeomRecon, we did not have an intended user or a domain expert to review our software. However, me and Dr. Spencer Smith were also lacking the knowledge and do not

know the expectation of the intender user or domain expert, this causes ambiguity in understanding the true requirements of AortaGeomRecon.

Finally, it is very challenging of understanding assurance cases with a limited time, and building the assurance cases for AortaGeomRecon was unclear for me. Gathering the evidences and support our arguments was not in my imagination at the beginning of the project, without truely understanding our goals of the project, I was not certain what I was really doing for this project. Until we have several pieces linking together, I was finally understanding and making more efforts in the right direction.

## 4.2 Future Works

In this section, we will discuss some possible future works that can continue to make AortaGeomRecon better, the first improvement can be done in segmentation algorithm, and the second improvement can finalize our assurance case.

### 4.2.1 Segmentation Algorithm

In this paper [13], we were able to discover a new segmentation algorithm that also needs a cropped volume and the aorta seeds to perform segmentation. However, it required less hyperparameters such as the parameters for SimpleITK's ThresholdSegmentationLevelSetsFilter. Using this algorithm effectively reduces the number of hyperparameters, which lead to a better and safer segmentation results.

### 4.2.2 Assurance Case

There is room for improvements on the arguments of the requirements of Aorta-GeomRecon. The correctness of the document is reviewed and approved by a domain expert, where there should be evidences that can support the argument.

# Appendix A

# Software Requirements Specification for AortaGeomRecon

# Software Requirements Specification for AortaGeomRecon

Jingyi Lin

July 2, 2023

# Contents

# Revision History

| Date | Version | Notes |
|---|---|---|
| 2023-02-12 | 1.0 | Notes |
| 2023-03-01 | 1.01 | Modified system context image, coordinate systems, and goal statements. |
| 2023-04-29 | 1.02 | Added requirements, instance models, data definitions |
| 2023-06-05 | 1.03 | Added Traceability Matrices |
| 2023-06-18 | 1.04 | Include the missing sections, modified the equations of DD, and IM. Added 4 new NFRs. |

# 1 Reference Material

This section records information for easy reference.

## 1.1 Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit and the SI name.

## 1.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units. The choice of symbols was made to be consistent with existing documentation for 3D Slicer program. The symbols are listed in alphabetical order.

| symbol | type | description |
|---|---|---|
| $m$ | $\mathbb{N}$ | The first dimension of the segmentation volume. |
| $m_i$ | $\mathbb{N}$ | The first dimension of $V_{\text{in}}$. |
| $m_o$ | $\mathbb{N}$ | The first dimension of $V_{\text{out}}$. |
| $n$ | $\mathbb{N}$ | The second dimension of the segmentation volume. |
| $n_i$ | $\mathbb{N}$ | The second dimension of $V_{\text{in}}$. |
| $n_o$ | $\mathbb{N}$ | The second dimension of $V_{\text{out}}$. |
| $p$ | $\mathbb{N}$ | The third dimension of the segmentation volume. |
| $p_i$ | $\mathbb{N}$ | The third dimension of $V_{\text{in}}$. |
| $p_o$ | $\mathbb{N}$ | The third dimension of $V_{\text{out}}$. |
| *slice* | $\mathbb{R}^{m\times n}$ | A slice is a 2 dimensional image view from the superior to inferior direction. |
| $v$ | $\mathbb{R}$ | A voxel reports the intensity of a single point on a grey-scale three-dimensional images. |
| *HIGH* | $\mathbb{N}$ | A high intensity values means 1 on a scale of 0 and 1, or 255 on a scale of 0 to 255. |
| *LOW* | $\mathbb{N}$ | A low intensity values means 0 on a scale of 0 and 1, or 0 on a scale of 0 to 255. |
| *Seed_a* | $\mathbb{N}^3$ | The initial ascending aorta centre coordinates. |
| *Seed_d* | $\mathbb{N}^3$ | The initial descending aorta centre coordinates. |
| *Start* | $\mathbb{N}^3$ | A coordinate indicates the indexes of a starting voxel. |
| $V$ | $\mathbb{R}^{m\times n\times p}$ | Volume formed by a sequence of slice |

## 1.3 Abbreviations and Acronyms

| symbol | description |
|---|---|
| A | Assumption |
| AortaGeomRecon | Aorta Geometry Reconstructor |
| DD | Data Definition |
| DICOM | Digital Imaging and Communications in Medicine |
| GD | General Definition |
| GS | Goal Statement |
| IM | Instance Model |
| LC | Likely Change |
| PS | Physical System Description |
| R | Requirement |
| SRS | Software Requirements Specification |
| T | Theoretical Model |

# 2 Introduction

This document provides an overview of the Software Requirements Specification (SRS) for the AortaGeomRecon. AortaGeomRecon provides a semi-automatically aorta segmentation method, a highly customizable aorta segmentation module, and an interactive user interface to apply the segmentation workflow.

One of the existing methods involves the use ITK-Snap software and its segmentation module. First, the user needs to convert the DICOM data files (or any other file type) to VTK file. Then, the user can load the VTK file to ITK-Snap, and use its segmentation module to perform aorta segmentation. This segmentation method lets user initiate several voxels within the aorta volume and expand with a user's given size in each iteration. After the aorta volume has been filled by the "bubble", the user needs to cut the parts that are not within the aorta.

## 2.1 Purpose of Document

The main purpose of this document is to provide sufficient information to understand what AortaGeomRecon module does. The goals and theoretical models used in the AortaGeomRecon segmentation module implementation are provided, with an emphasis on explicitly identifying assumptions and unambiguous definitions.

## 2.2 Scope of Requirements

The scope of requirements only covers for the segmentation of the organ, more specifically the ascending aorta, the aortic curvature and the descending aorta. The requirements assume that the source of the data is accurate, and the user can manipulate (read, change dimensions) the data.

## 2.3 Characteristics of Intended Reader

The readers of the SRS should have taken the university level introduction to computational mathematic course, and be capable of understand the mathematical notation in the instance model section. The readers might have taken the university level introduction to software engineering course, have learned at least the waterfall software development model, and understands the purpose of the software specification requirement document, and other documents.

## 2.4 Organization of Document

The organization of this document follows the template for an SRS for scientific computing software proposed by Koothoor (2013) and Smith and Lai (2005). The presentation follows the standard pattern of presenting goals, theories, definitions and assumptions. The goal

statements are refined to the theoretical models, and theoretical models to the instance models. For readers that would like a more bottom-up approach, they can start reading the instance models in Section 4.2.6 and trace back to find any additional information they require.

# 3 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics and lists the system constraints.

## 3.1 System Context

Figure 1 shows the system context. A circle represents an external entity outside the software, the user in this case. A rectangle represents the software system itself. Arrows are used to show the data flow between the system and its environment.

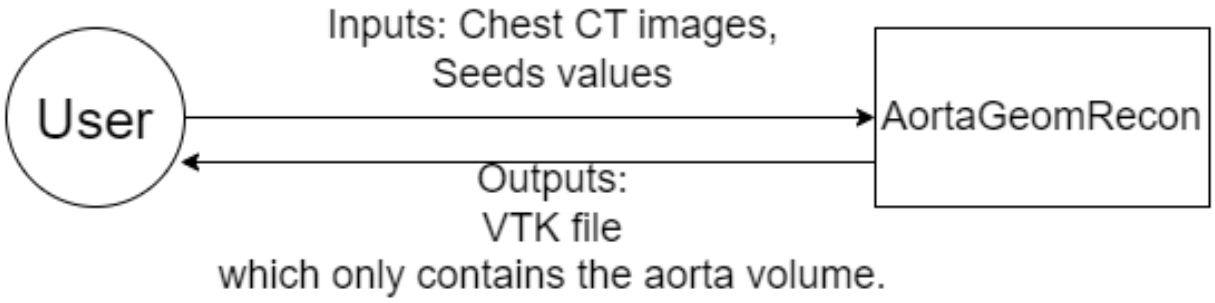



Figure 1: System Context

- User Responsibilities:
  - Provide the input data to the system
  - Ensure the input meets the necessary assumptions
  - Verify the result meets their requirements, otherwise repeat the process with a different seed values.
- AortaGeomRecon Responsibilities:
  - Provide DICOM data reader which can take a path to a folder containing DICOM files.

- Provide crop functionality to easily select a region of interest.
- Provide simple interactions to obtain and store the users' inputs. This includes a data probe to read voxel location which stored as a coordinate, and text inputs for real numbers.
- Provide visualization on the result data.

## 3.2 User Characteristics

The end user of AortaGeomRecon should have taken the university level anatomy introduction course, and be capable of finding the center of the descending aorta and the ascending aorta.

## 3.3 System Constraints

There are no system constraints of AortaGeomRecon.

# 4 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved. This is followed by the solution characteristics specification, which presents the assumptions, theories, definitions and finally the instance models.

## 4.1 Problem Description

The main purpose of AortaGeomRecon is to semi-automatically segment a 3D aorta geometry from a chest CT scan.

### 4.1.1 Organ Segmentation

Organs are the body's recognizable structures (for example, the heart, lungs, liver, eyes, and stomach) that perform specific functions. Figure 2 below shows all the organs within a human body. The organ segmentation or the organ boundary segmentation is useful for orientation and identification of the regions of interests inside the organ during the diagnostic or treatment procedure. The aorta segmentation is important for aortic calcification quantification and to guide the segmentation of other central vessels. Villa-Forte (2022)

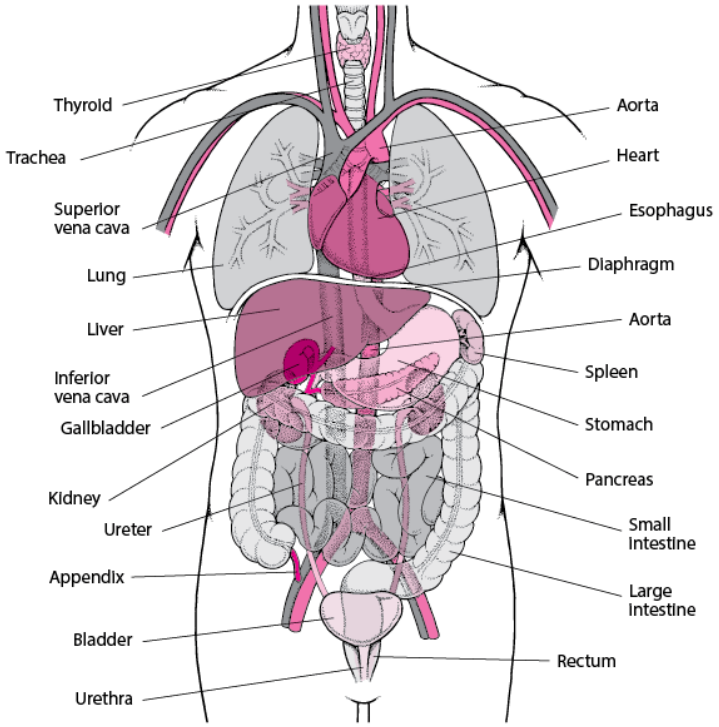



Figure 2: Human organs Villa-Forte (2022)

### 4.1.2 Coordinate Systems

This subsection provides a list of terms that are used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements. Nejad (2017)

While working with medical images, it is necessary to be familiar with the different coordinate systems of the medical literature and how data (voxels' orientation) is interpreted in different medical and nonmedical software. Each coordinate system uses one or more numbers (coordinates) to uniquely determine the position of a point (in the medical context, we refer to each point as a voxel). The purpose of this section is to introduce some coordinate systems related to the medical imaging. There are different coordinate systems to represent data. A knowledge of the following coordinate systems is needed to work with the medical images.

**Cartesian Coordinate System** A Cartesian coordinate system is a coordinate system that specifies each point uniquely in a 2D plane by a pair of numerical coordinates or in a 3D space by three numerical coordinates. We assume a right-hand Cartesian coordinate system throughout this document.

**World Coordinate System** World Coordinate System (WCS) is a Cartesian coordinate system that describes the physical coordinates associated with a model such as an MRI scanner or a patient. While each model has its own coordinate system, without a universal coordinate system such as WCS, they cannot interact with each other. For model interaction to be possible, their coordinate systems must be transformed into the WCS. Figure 3 shows the WCS corresponding space and axes.

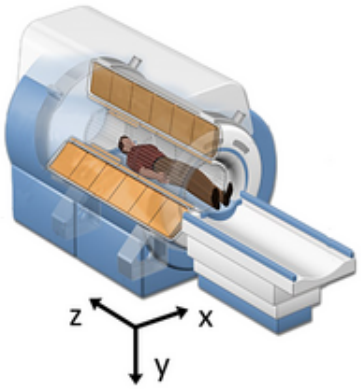
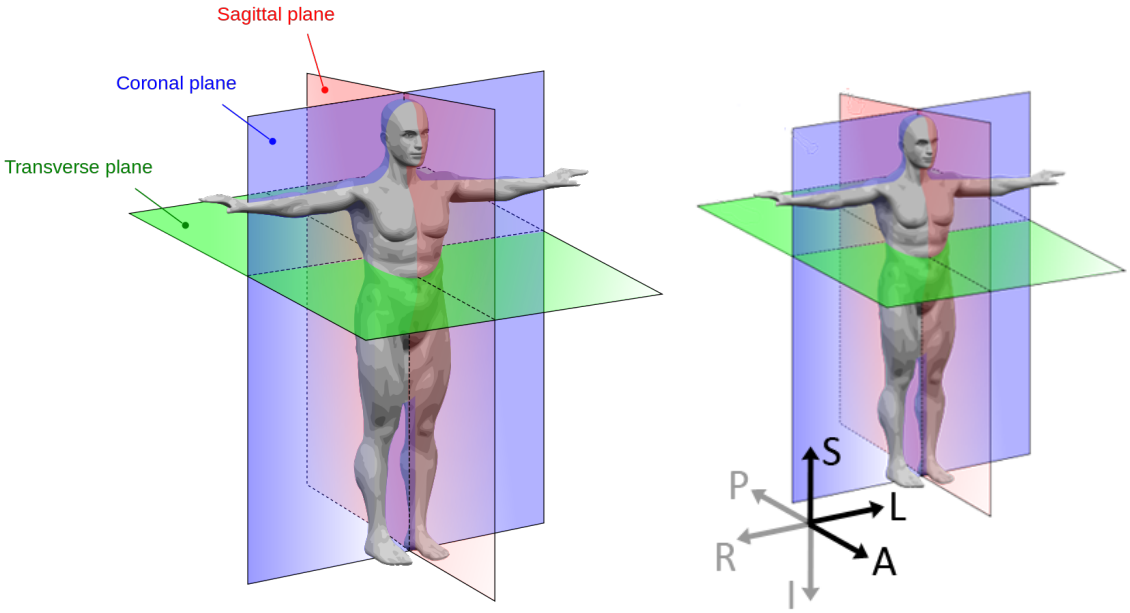



Figure 3: World Coordinate System Space and Axes sli (2014)

**Anatomical Coordinate System** Anatomical coordinate system, also known as patient coordinate system, is a right-handed 3D coordinate system that describes the standard anatomical position of a human using the following 3 orthogonal planes:

- Axial / Transverse plane: is a plane parallel to the ground that separates the body into head (superior) and tail (inferior) positions.
- Coronal / Frontal plane: is a plane perpendicular to the ground that divides the body into front (anterior) and back (posterior) positions.
- Sagittal / Median plane: is a plane that divides the body into right and left positions.

Figure 4 shows this coordinate system.




(a) Anatomical Coordinate System (b) Space and Axes

Figure 4: Anatomical Coordinate System Space and Axes sli (2014)

Medical applications follow an anatomical coordinate system to store voxels in sequences. Depending on how the data is stored, this coordinate system can be divided into different bases. The most common ones are:

- LPS Coordinate System:

  The LPS coordinate system is used in DICOM images. In this system, voxels are ordered from left to right in a row, rows are ordered from posterior to anterior, and slices are stored from inferior to superior. LPS stands for Left-Posterior-Superior which indicates the directions that spatial axes are increasing.

- RAS Coordinate System:

  The RAS coordinate system is the preferred basis for Neurological applications such as 3dfim+, and 3D Slicer. RAS stands for Right-Anterior-Superior is similar to LPS with the first two axes flipped.

**Image Coordinate System** To specify locations in an image we need to know to which coordinate system it is referenced. Different software may use different orders as their index convention.
Each of the coordinate systems mentioned above are used by different systems.

### 4.1.3 Physical System Description

We do not study the physical system for the images or how the data is actually generated.

### 4.1.4 Goal Statements

Given the DICOM image that includes patient's chest, the descending aorta center voxel coordinate, and the ascending aorta center voxel coordinate, the goal statements are:

GS1: Extract the three-dimensional segmentation of the aorta.

## 4.2 Solution Characteristics Specification

### 4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [T], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

A1: The 3D image provided by the user must contain a visually distingushable aorta volume [IM1].

A2: User should select a valid region of interest [IM2].

A3: User should input a singular volume (3 dimensional image) even if the data format supports the 4th dimension (time) [IM1].

### 4.2.2 Theoretical Models

There are no theoretical models used in this document.

### 4.2.3 General Definitions

There are no general definition used in this document.

### 4.2.4 Data Definitions

This section collects and defines all the data needed to build the instance models.

| Number | DD1 |
|---|---|
| Label | **Voxel** |
| Symbol | $v : \mathbb{R}$ |
| SI Units | - |
| Equation | - |
| Description | A slice (DD2) consists of $n \times n$ voxels. A real number is assigned to each voxel to reports the intensity on a grey-scale image. |
| Sources | Nejad (2017) |
| Ref. By | DD2 |

| Number | DD2 |
|---|---|
| Label | **Image/Slice** |
| Symbol | $slice : \mathbb{R}^{m \times n}$ |
| SI Units | - |
| Equation | - |
| Description | A visual representation that is using only two spatial dimensions with a sequence of arrays where a voxel (DD1) represents the color or intensity. Each move in the transverse plane (Figure 4) is considered as one slice |
| Sources | Nejad (2017) |
| Ref. By | DD3 |

| Number | DD3 |
|---|---|
| Label | **Volume** |
| Symbol | $V : \mathbb{R}^{m \times n \times p}$ |
| SI Units | - |
| Equation | - |
| Description | A three-dimensional image is a sequence of some images/slices (DD2). |
| Sources | - |
| Ref. By | IM1 |

### 4.2.5 Data Types

There are no additional data types used in this document.

### 4.2.6 Instance Models

This section transforms the problem defined in Section 4.1 into one which is expressed in mathematical terms. It uses concrete symbols defined in Section 4.2.4 to replace the abstract symbols in the models. There are no theoretical models or general definitions used in this document.

The goals GS1 are solved by finding IM1 and perform IM2 on the aorta.

| Number | IM1 |
|---|---|
| Label | **Region of interest** |
| Inputs | $V_{\text{in}} : \mathbb{R}^{m_i \times n_i \times p_i}$ , $Start : \mathbb{N}^3$, $m_o, n_o, p_o : \mathbb{N}$, with the following constraints: $$0 \leq Start[0] < (m_i - 1)$$ $$0 \leq Start[1] < (n_i - 1)$$ $$0 \leq Start[2] < (p_i - 1)$$ $$0 < m_o \leq (m_i - Start[0])$$ $$0 < n_o \leq (n_i - Start[1])$$ $$0 < p_o \leq (p_i - Start[2])$$ |
| Output | $V_{\text{out}} : \mathbb{R}^{m_o \times n_o \times p_o}$ such that $$\forall(i, j, k : \mathbb{N} \mid i \in [Start[0]..Start[0] + m_o] \wedge j \in [Start[1]..Start[1] + n_o] \wedge k \in [Start[2]..Start[2] + p_o] : V_{\text{out}}[i][j][k] = V_{\text{in}}[i][j][k])$$ |
| Description | The regions of interest is a subset (shaped like a box) of the 3D $V_{\text{out}}$. This subset contains the anatomical structure that the users wants to read, process or extract. |
| Sources | |
| Ref. By | IM2 |

| Number | IM2 |
|---|---|
| Label | **Segmentation** |
| Input | $V_{\text{in}} : \mathbb{R}^{m \times n \times p}$, $Seed\_a : \mathbb{N}^3$, $Seed\_d : \mathbb{N}^3$ |
| Output | $V_{\text{out}} : \mathbb{R}^{m \times n \times p}$ such that<br>$\forall (i, j, k : \mathbb{N} \mid$<br>$i \in [0..m-1] \wedge\ j \in [0..n-1] \wedge\ k \in [0..p-1] :$<br>$(V_{\text{in}}[i,j,k] \in \text{structure} \implies V_{\text{out}}[i,j,k] = HIGH \mid$<br>$V_{\text{in}}[i,j,k] \notin \text{structure} \implies V_{\text{out}}[i,j,k] = LOW))$<br>The inputs $Seed\_a$ and $Seed\_d$ are used to determine whether a given element of $V_{\text{in}}$ is in structure or not. |
| Description | The process of extract an anotomical structure from the original 3D volume. The extracted anotomical structure is represented with high intensity pixel value. The rest of the image should have a lower intensity pixel value. The segmentation needs the region of interset from IM1 to process less noise data. A seed is what the algorithm needed as the inputs to perform segmentation, the type of seed is different among different algorithm. The seeds in this section are the centre coordinate of the descending aorta and the ascending aorta. The yellow dots shown in Figure 5 are the example of the seed. |
| Sources | |
| Ref. By | R3, LC1 |

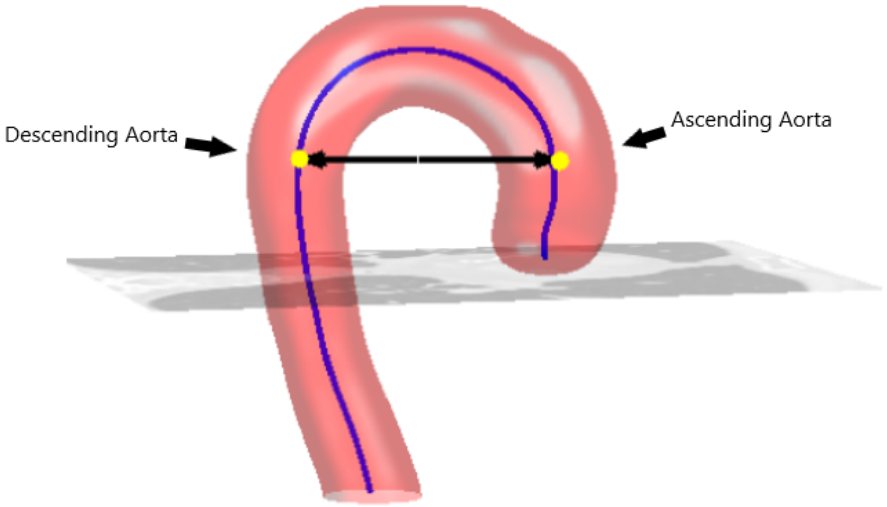



Figure 5: Aorta Seeds Kurugol et al. (2012)

#### 4.2.7 Input Data Constraints

The only software constraint is the input volume data. It must be an acceptable file type to the system processing the data. For example, using ITK-Snap software to perform organ segmentation, the input data must be of VTK file.

#### 4.2.8 Properties of a Correct Solution

A correct solution cannot be measured, but it can be confirmed by visually comparing the intersection of the extracted anotomical structure and the original volume.

# 5 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

## 5.1 Functional Requirements

R1: Input the following functions, data and parameters:

| symbol | description |
|---|---|
| $V$ | CT Scans volume (DD3) |
| $Seed\_a$ | The seed of ascending aorta centre coordinate (IM2) |
| $Seed\_d$ | The seed of descending aorta centre coordinate (IM2) |

R2: Use the volume in R1 to create a second volume, the region of interest (IM1) that contains all voxels of the aorta.

R3: Perform segmentation (IM2) on the volume created in R2.

R4: Visualize a volume (DD3).

## 5.2 Nonfunctional Requirements

NFR1: **Usability** AortaGeomRecon allows a user that meets the user characteristics (Section 3.2) to import any DICOM files, input the required parameters, and begin the segmentation effortlessly. The number of steps it takes using AortaGeomRecon should be at least 30% less than the number of steps it takes by using ITK-Snap (bubble method mentioned in Section 2).

NFR2: **Safety** For a valid image, the AortaGeomRecon provides a correct solution, or no answer.

NFR3: **Learnability** The user interface and documentation should allow a user that meets the user characteristics (Section 3.2) to learn how to do an aorta segmentation in at least 30% of the time it takes to learn and use ITK-Snap (bubble method mentioned in Section 2).

NFR4: **Accuracy** For a given image the segmentation found by AortaGeomRecon should match that found by an expert using ITK-Snap. Whether to two segmentations match is something that would be judged by a medical imaging expert.

NFR5: **Consistency** The coordinate system may be modified through the calculations, but any transformations will not alter the meaning of the data.

Other NFRs that might be discussed in the future include verifiability, and reusability.

# 6 Likely Changes

LC1: IM2 There are various segmentation algorithms, each has a different procedure and inputs.

# 7 Unlikely Changes

UC1: IM1 The method to retrieve a region of interest from a volume is fixed.

# 8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an "X" may have to be modified as well. Table 2 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 3 shows the dependencies of instance models, requirements, and data constraints on each other. Table 4 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions.

The purpose of the traceability graphs is also to provide easy references on what has to be additionally modified if a certain component is changed. The arrows in the graphs represent dependencies. The component at the tail of an arrow is depended on by the component at

the head of that arrow. Therefore, if a component is changed, the components that it points to should also be changed.

| | DD1 | DD2 | DD3 | IM1 | IM2 |
|---|---|---|---|---|---|
| DD1 | | | | | |
| DD2 | X | | | | |
| DD3 | | X | | | |
| IM1 | | | X | | |
| IM2 | | | | X | |

Table 2: Traceability Matrix Showing the Connections Between Items of Different Sections

| | IM1 | IM2 | R1 | R2 | R3 | R4 | NFR1 | NFR2 | NFR3 | NFR4 | NFR5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| IM1 | | | | X | | | | | | | |
| IM2 | | | | | X | | | | | | |
| R1 | | X | | | | | | | | | |
| R2 | X | | | | | | | | | | |
| R3 | | X | | | | | | | | | |
| R4 | | | | | | | X | | | | |
| NFR1 | | | X | X | X | X | | | X | | |
| NFR2 | | X | | | | | | | | | |
| NFR3 | | | | X | X | X | X | | | | |
| NFR4 | | X | | | | | | | | | |
| NFR5 | | X | | | | | | | | | |

Table 3: Traceability Matrix Showing the Connections Between Requirements and Instance Models

| | A1 | A2 | A3 |
|---|---|---|---|
| DD1 | | | |
| DD2 | | | |
| DD3 | | | X |
| IM1 | X | | X |
| IM2 | | X | X |
| LC1 | X | X | X |
| UC1 | | | X |

Table 4: Traceability Matrix Showing the Connections Between Assumptions and Other Items

# 9 Referance

# References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Nirmitha Koothoor. A document drive approach to certifying scientific computing software. Master's thesis, McMaster University, Hamilton, Ontario, Canada, 2013. URL http://hdl.handle.net/11375/13266.

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# Appendix B

# Module Guide for AortaGeomRecon

# Module Guide for AortaGeomRecon

Jingyi Lin

July 5, 2023

# 1 Revision History

| Date | Version | Notes |
|---|---|---|
| 2022-10-18 | 1.0 | First draft of Module Guide |
| 2023-04-21 | 1.1 | Second draft of Module Guide |
| 2023-07-05 | 1.2 | Added Traceability matrix between modules and source code. Added User Hierarchy between modules. |

# 2 Reference Material

This section records information for easy reference.

## 2.1 Abbreviations and Acronyms

| Symbol | description |
|---|---|
| AC | Anticipated Change |
| DAG | Directed Acyclic Graph |
| M | Module |
| MG | Module Guide |
| OS | Operating System |
| R | Requirement |
| NFR | Non-Functional requirements |
| SC | Scientific Computing |
| SRS | Software Requirements Specification |
| AortaGeomRecon | Aorta Geometry Reconstruction |
| UC | Unlikely Change |

# Contents



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# 3 Introduction

Decomposing a system into modules is a commonly accepted approach to developing software. A module is a work assignment for a programmer or programming team (Parnas et al., 1984). We advocate a decomposition based on the principle of information hiding (Parnas, 1972). This principle supports design for change, because the "secrets" that each module hides represent likely future changes. Design for change is valuable in SC, where modifications are frequent, especially during initial development as the solution space is explored.

Our design follows the rules laid out by Parnas et al. (1984), as follows:

- System details that are likely to change independently should be the secrets of separate modules.
- Each data structure is implemented in only one module.
- Any other program that requires information stored in a module's data structures must obtain it by calling access programs belonging to that module.

After completing the first stage of the design, the Software Requirements Specification (SRS), the Module Guide (MG) is developed (Parnas et al., 1984). The MG specifies the modular structure of the system and is intended to allow both designers and maintainers to easily identify the parts of the software. The potential readers of this document are as follows:

- New project members: This document can be a guide for a new project member to easily understand the overall structure and quickly find the relevant modules they are searching for.
- Maintainers: The hierarchical structure of the module guide improves the maintainers' understanding when they need to make changes to the system. It is important for a maintainer to update the relevant sections of the document after changes have been made.
- Designers: Once the module guide has been written, it can be used to check for consistency, feasibility and flexibility. Designers can verify the system in various ways, such as consistency among modules, feasibility of the decomposition, and flexibility of the design.

The rest of the document is organized as follows. Section 4 lists the anticipated and unlikely changes of the software requirements. Section 5 summarizes the module decomposition that was constructed according to the likely changes. Section 6 specifies the connections between the software requirements and the modules. Section 7 gives a detailed description of the modules. Section 8 includes two traceability matrices. One checks the completeness of the design against the requirements provided in the SRS. The other shows the relation between anticipated changes and the modules. Section 9 describes the use relation between modules.

# 4 Anticipated and Unlikely Changes

This section lists possible changes to the system. According to the likeliness of the change, the possible changes are classified into two categories. Anticipated changes are listed in Section 4.1, and unlikely changes are listed in Section 4.2.

## 4.1 Anticipated Changes

Anticipated changes are the source of the information that is to be hidden inside the modules. Ideally, changing one of the anticipated changes will only require changing the one module that hides the associated decision. The approach adapted here is called design for change.

**AC1:** The specific hardware on which the software is running.

**AC2:** The format of the initial input data.

**AC3:** The algorithm to segment the aorta.

**AC4:** The data structures to store the input parameters required to execute the algorithm.

**AC5:** The methods to create a user interface.

**AC6:** The methods to retrieve a region of interest.

**AC7:** The methods to visualize a volume.

**AC8:** How the overall control of the calculations is orchestrated.

**AC9:** The format of the final output data.

...

## 4.2 Unlikely Changes

The module design should be as general as possible. However, a general system is more complex. Sometimes this complexity is not necessary. Fixing some design decisions at the system architecture stage can simplify the software design. If these decision should later need to be changed, then many parts of the design will potentially need to be modified. Hence, it is not intended that these decisions will be changed.

**UC1:** Input/Output devices (Input: File and/or Keyboard, Output: File, Memory, and/or Screen).

**UC2:** The input volume data's dimensionality is unlikely to change.

...

# 5 Module Hierarchy

This section provides an overview of the module design. Modules are summarized in a hierarchy decomposed by secrets in Table 1. The modules listed below, which are leaves in the hierarchy tree, are the modules that will actually be implemented.

**M1:** Hardware-Hiding Module

**M2:** Input Format Module

**M3:** Input Parameter Module

**M4:** Control Module

**M5:** GUI Module

**M6:** Volume Visualization Module

**M7:** Crop Volume Module

**M8:** Aorta Segmentation Module

**M9:** Image Processing Module

**M10:** Multidimensional Array Processing Module

**M11:** Digital Enhancement Module

...

# 6 Connection Between Requirements and Design

The design of the system is intended to satisfy the requirements developed in the SRS. In this stage, the system is decomposed into modules. The connection between requirements and modules is listed in Table 2.

# 7 Module Decomposition

Modules are decomposed according to the principle of "information hiding" proposed by Parnas et al. (1984). The *Secrets* field in a module decomposition is a brief statement of the design decision hidden by the module. The *Services* field specifies *what* the module will do without documenting *how* to do it. For each module, a suggestion for the implementing software is given under the *Implemented By* title. If the entry is *OS*, this means that the module is provided by the operating system or by standard programming language libraries. *AortaGeomRecon* means the module will be implemented by the AortaGeomRecon software.

Only the leaf modules in the hierarchy have to be implemented. If a dash (–) is shown, this means that the module is not a leaf and will not have to be implemented.

| Level 1 | Level 2 | Level 3 |
|---|---|---|
| Hardware-Hiding Module | | |
| Behaviour-Hiding Module | Input Format Module | |
| | Input Parameter Module | |
| | Control Module | |
| | Volume Visualization Module | |
| | Crop Module | |
| | Aorta Segmentation Module | |
| | Digital Enhancement Module | |
| Software Decision Module | GUI Module | |
| | Image Processing Module | |
| | Multi-Dimensional Array Processing Module | |

Table 1: Module Hierarchy

## 7.1 Hardware Hiding Modules (M1)

**Secrets:** The data structure and algorithm used to implement the virtual hardware.

**Services:** Serves as a virtual hardware used by the rest of the system. This module provides the interface between the hardware and the software. So, the system can use it to display outputs or to accept inputs.

**Implemented By:** OS

## 7.2 Behaviour-Hiding Module

**Secrets:** The contents of the required behaviors.

**Services:** Includes programs that provide externally visible behavior of the system as specified in the software requirements specification (SRS) documents. This module serves as a communication layer between the hardware-hiding module and the software decision module. The programs in this module will need to change if there are changes in the SRS.

**Implemented By:** –

### 7.2.1 Input Format Module (M2)

**Secrets:** The format and structure of the input data.

**Services:** Converts the input data into the data structure used by the input parameters module.

**Implemented By:** AortaGeomRecon

**Source:** AortaGeomReconDisplayModuleLogic module's process function

#### 7.2.2 Input Parameter Module (M3)

**Secrets:** The data structure for input parameters, how the values are input and how the values are verified. The load and verify secrets are isolated to their own access programs.

**Services:** Gets input from user, stores input and verifies that the input parameters comply with physical and software constraints. Throws an error if a parameter violates a physical constraint. Throws a warning if a parameter violates a software constraint. Stored parameters can be read individually, but write access is only to redefine the entire set of inputs.

**Implemented By:** AortaGeomRecon

**Source:** AortaSegmenter class' atributes

#### 7.2.3 Control Module (M4)

**Secrets:** The algorithm for coordinating the running of the program.

**Services:** Provides the main program's entry point, the ability to jump from a program state to another.

**Implemented By:** AortaGeomRecon

**Source:** AortaGeomReconDisplayModuleWidget module

#### 7.2.4 Volume Visualization Module (M6)

**Secrets:** The methods which allow users to visualize a 3D Volume.

**Services:** Display the aorta images and vtk 3D geometry.

**Implemented By:** 3D Slicer

#### 7.2.5 Crop Module (M7)

**Secrets:** The parameters, libraries to retrieve a region of interest from a volume.

**Services:** Import the necessary libraries, store the input parameter, and coordinate the uses of these data and libraries to retrieve a region of interest.

**Implemented By:** 3D Slicer

#### 7.2.6 Aorta Segmentation Module (M8)

**Secrets:** The parameters, libraries to perform segmentation.

**Services:** Import the necessary libraries, store the input parameter, and coordinate the uses of these data and libraries to perform segmentation.

**Implemented By:** AortaGeomRecon

**Source:** AortaSegmenter module

#### 7.2.7 Digital Enhancement Module (M11)

**Secrets:** The algorithm to enhance a digital image.

**Services:** Accepts a 2D image, output a 2D image with the same dimension as the input, improves visual quality of its greyscale image

**Implemented By:** AortaGeomRecon

**Source:** AortaGeomReconDisplayModuleLogic's transform_image function

### 7.3 Software Decision Module

**Secrets:** The design decision based on mathematical theorems, physical facts, or programming considerations. The secrets of this module are *not* described in the SRS.

**Services:** Includes data structure and algorithms used in the system that do not provide direct interaction with the user.

**Implemented By:** –

#### 7.3.1 GUI Module (M5)

**Secrets:** The necessary library/framework to build a GUI software.

**Services:** Povide Graphical User Interface for user to write/read inputs, and send commands to the program. It could include the rendering a windows, inputs, keyboard and mouse interaction with the GUI elements.

**Implemented By:** 3D Slicer

### 7.3.2 Image Processing Module (M9)

**Secrets:** The libraries and the APIs to perform image analysis, and image segmentation.

**Services:** Provides useful APIs such as ThresholdSegmentationLevelSetsImageFilter, LabelStatisticImageFilter to perform aorta segmentation.

**Implemented By:** SITK

### 7.3.3 Multi-Dimensional Array Processing Module(M10)

**Secrets:** The libraries and the APIs to perform element-wise mathematic operations on multidimensional array.

**Services:** Provides useful APIs such as calculating the max, min, average of multidimensional array. NumPy.where function provides the search in the multidimensional array functionality which will return any element's indexes if it satisfies the given condition.

**Implemented By:** NumPy

# 8 Traceability Matrix

This section shows two traceability matrices: between the modules and the requirements and between the modules and the anticipated changes. The list of requirements can refer to the AortaGeomRecon's SRS. Lin (2023)

| **Req.** | **Modules** |
|---|---|
| R1 | M1, M2, M3, M4 |
| R2 | M3, M7 |
| R3 | M8, M9, M10 |
| R4 | M6 |
| NFR1 | M3, M4, M5 |
| NFR2 | M4, M8, M9, M10 |
| NFR3 | M3, M4, M5 M6, M7, M8 |
| NFR4 | M7, M8, M9, M10 |
| NFR5 | M3 |

Table 2: Trace Between Requirements and Modules

| **AC** | **Modules** |
|---|---|
| AC1 | M1 |
| AC2 | M2 |
| AC3 | M8 |
| AC4 | M3 |
| AC5 | M5 |
| AC6 | M7 |
| AC7 | M6 |
| AC8 | M4 |
| AC9 | M9, M10 |

Table 3: Trace Between Anticipated Changes and Modules

| Modules | Code |
|---|---|
| M1 | - |
| M2 Input Format Module | |

```
# AortaGeomReconDisplayModule.py
# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModule.py#L543-L554
stop_limit = self._parameterNode.GetParameter("stop_limit")
threshold_coef = self._parameterNode.GetParameter("threshold_coef")
rms_error = self._parameterNode.GetParameter("rms_error")
no_ite = self._parameterNode.GetParameter("no_ite")
curv_scaling = self._parameterNode.GetParameter("curv_scaling")
prop_scaling = self._parameterNode.GetParameter("prop_scaling")
kernel_size = self._parameterNode.GetParameter("kernel_size")

# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModule.py#L824-L855
def process(self, des_seed, asc_seed, stop_limit, threshold_coef,
            kernel_size, rms_error, no_ite, curvature_scaling,
            propagation_scaling, debug):
    """Convert the parameters to the correct format and
    call begin_segmentation from AortaSegmenter.

    Returns:
        SITK::image: The processing image, or the segmentation label
            image
    """
    des_seed = des_seed.split(",")
    asc_seed = asc_seed.split(",")
    asc_seed = [int(i) for i in asc_seed]
    des_seed = [int(i) for i in des_seed]
    now = datetime.now()
    if not self._cropped_image:
        volume = slicer.mrmlScene.GetFirstNode(
                "cropped", None, None, False)
        self.transform_image(volume)
    logging.info(f"{now} processing")
    segmenter = AortaSegmenter(
        cropped_image=self._cropped_image, des_seed=des_seed,
        asc_seed=asc_seed, stop_limit=float(stop_limit),
        threshold_coef=float(threshold_coef),
        kernel_size=int(float(kernel_size)),
        rms_error=float(rms_error), no_ite=int(no_ite.split(".")[0]),
        curvature_scaling=float(curvature_scaling),
        propagation_scaling=float(propagation_scaling), debug=debug
    )
    segmenter.begin_segmentation()
    now = datetime.now()
    logging.info(f"{now} Finished processing")
    return segmenter.processing_image
```

M3 Input Parameter Module

```
# AortaSegmenter.py
# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModuleLib/AortaSegmenter.py#L53-L82
def __init__(
            self, cropped_image, des_seed, asc_seed, stop_limit=10,
            threshold_coef=3, kernel_size=6, rms_error=0.02, no_ite=600,
            curvature_scaling=2, propagation_scaling=0.5, debug=False
    ):
    self._des_seed = des_seed
    self._des_prev_centre = des_seed[:2]
    self._asc_seed = asc_seed
    self._asc_prev_centre = asc_seed[:2]
    self._stop_limit = stop_limit
    self._threshold_coef = threshold_coef
    self._cropped_image = cropped_image
    self._kernel_size = kernel_size
    self._debug_mod = debug
    self._stats_filter = sitk.LabelStatisticsImageFilter()
    self._segment_filter = sitk.ThresholdSegmentationLevelSetImageFilter
        ()
    self._segment_filter.SetMaximumRMSError(rms_error)
    self._segment_filter.SetNumberOfIterations(no_ite)
    self._segment_filter.SetCurvatureScaling(curvature_scaling)
    self._segment_filter.SetPropagationScaling(propagation_scaling)
    self._segment_filter.ReverseExpansionDirectionOn()
    self._k = 2
```

M4 Control Module

```
# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModule.py#L537-L583
def onApplyButton(self):
    """
    Go to next phase if on phase 1 crop aorta or perform segmentation if
        on phase 2 aorta segmentation.
    """

    with slicer.util.tryWithErrorDisplay(errorMessage, waitCursor=True):
        if self._parameterNode.GetParameter("phase") == "1":
            size = len(slicer.util.getNodes("*cropped*", useLists=True))
            if not size:
                logging.info("Cannot find cropped volume")
            else:
                self.showPhaseAS()
        elif self._parameterNode.GetParameter("phase") == "2":
            descAortaSeed = self._parameterNode.GetParameter(
                "descAortaSeed")
            ascAortaSeed = self._parameterNode.GetParameter(
                "ascAortaSeed")
            volume = sceneObj.GetFirstNode("cropped", None, None, False)
            self.logic.transform_image(volume)
            image = self.logic.process(
                descAortaSeed, ascAortaSeed, stop_limit,
                threshold_coef, kernel_size, rms_error, no_ite,
                curv_scaling, prop_scaling, self.ui.debugBox.checked
            )
            sitkUtils.PushVolumeToSlicer(
                image,
                name="Seg_th{}_k{}_c{}_p{}".format(
                    threshold_coef,
                    kernel_size,
                    curv_scaling,
                    prop_scaling),
                className="vtkMRMLScalarVolumeNode"
            )
```

M5 GUI Module

```
# AortaGeomReconDisplayModule.AortaGeomReconDisplayModuleWidget class
# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModule.py#L139-L245
class AortaGeomReconDisplayModuleWidget(ScriptedLoadableModuleWidget,
    VTKObservationMixin):
    def setup(self):
        ScriptedLoadableModuleWidget.setup(self)
        uiWidget = slicer.util.loadUI(self.resourcePath('UI/
            AortaGeomReconDisplayModule.ui'))  # noqa: E501
        self.layout.addWidget(uiWidget)
        self.ui = slicer.util.childWidgetVariables(uiWidget)
        uiWidget.setMRMLScene(slicer.mrmlScene)
        self.logic = AortaGeomReconDisplayModuleLogic()
        scene = slicer.mrmlScene
        self.crosshairNode = slicer.util.getNode("Crosshair")
        self.crosshairNode.AddObserver(
            slicer.vtkMRMLCrosshairNode.CursorPositionModifiedEvent,
            self.onMouseMoved
        )

        self.addObserver(scene, scene.StartCloseEvent, self.
            onSceneStartClose)
        self.addObserver(scene, scene.EndCloseEvent, self.onSceneEndClose
            )
        self.ui.ascAortaSeed.connect(
            "coordinatesChanged(double*)", self.
                updateParameterNodeFromGUI)
        self.ui.descAortaSeed.connect(
            "coordinatesChanged(double*)", self.
                updateParameterNodeFromGUI)
        self.ui.stopLimit.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)
        self.ui.kernelSize.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)
        self.ui.thresholdCoefficient.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)
        self.ui.rmsError.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)
        self.ui.noIteration.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)
        self.ui.curvatureScaling.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)
        self.ui.propagationScaling.connect(
            "valueChanged(double)", self.updateParameterNodeFromGUI)

        # Buttons
        self.ui.applyButton.connect('clicked(bool)', self.onApplyButton)
        self.ui.revertButton.connect('clicked(bool)', self.onRevertButton
            )
        self.ui.resetButton.connect('clicked(bool)', self.onResetButton)
        self.ui.skipButton.connect('clicked(bool)', self.onSkipButton)
        self.ui.getVTKButton.connect('clicked(bool)', self.onGetVTKButton
            )

        sliceDisplayNodes = slicer.util.getNodesByClass(
            "vtkMRMLSliceDisplayNode")
        for sliceDisplayNode in sliceDisplayNodes:
            sliceDisplayNode.SetIntersectingSlicesVisibility(1)

        sliceNodes = slicer.util.getNodesByClass('vtkMRMLSliceNode')
        for sliceNode in sliceNodes:
            sliceNode.Modified()
        self.initializeParameterNode()
```

| | |
|---|---|
| M6 Volume Visualization Module | 3D Slicer's Volume Rendering Module<br><br>3D Slicer's Volume Rendering Source Code |
| M7 Crop Volume Module | 3D Slicer's Crop Volume Module<br><br>3D Slicer's Crop Volume Module Source Code |
| M8 Aorta Segmentation Module | AortaSegmenter class |
| M9 Image Processing Module | SimpleITK |
| M10 Multi-Dimensional Array Processing Module | NumPy |
| M11 Digital Enhancement Module | |

```
# AortaGeomReconDisplayModule.py
# https://github.com/smiths/aorta/blob/main/src/SlicerExtension/
    AortaGeometryReconstructor/AortaGeomReconDisplayModule/
    AortaGeomReconDisplayModule.py#L739-L769
    def transform_image(self, cropped_volume):
        """
        Histogram Equalization for Digital Image Enhancement.
        https://levelup.gitconnected.com/introduction-to-histogram-
            equalization-for-digital-image-enhancement-420696db9e43
        """
        cropped_image = sitkUtils.PullVolumeFromSlicer(cropped_volume)
        img_array = sitk.GetArrayFromImage(
            (sitk.Cast(sitk.RescaleIntensity(cropped_image), sitk.
                sitkUInt8)))
        histogram_array = np.bincount(img_array.flatten(), minlength=256)
        num_pixels = np.sum(histogram_array)
        histogram_array = histogram_array/num_pixels
        chistogram_array = np.cumsum(histogram_array)
        transform_map = np.floor(255 * chistogram_array).astype(np.uint8)
        img_list = list(img_array.flatten())
        eq_img_list = [transform_map[p] for p in img_list]
        eq_img_array = np.reshape(np.asarray(eq_img_list), img_array.
            shape)
        eq_img = sitk.GetImageFromArray(eq_img_array)
        eq_img.CopyInformation(cropped_image)
        median = sitk.MedianImageFilter()
        median_img = sitk.Cast(median.Execute(eq_img), sitk.sitkUInt8)
        self._cropped_image = median_img
```

Table 4: Trace Between Modules and Code

# 9 Use Hierarchy Between Modules

In this section, the uses' hierarchy between modules is provided. Parnas (1978) said of two programs A and B that A *uses* B if correct execution of B may be necessary for A to complete the task described in its specification. That is, A *uses* B if there exist situations in which the correct functioning of A depends upon the availability of a correct implementation of B. Figure 1 illustrates the use relation between the modules. It can be seen that the graph is a directed acyclic graph (DAG). Each level of the hierarchy offers a testable and usable subset of the system, and modules in the higher level of the hierarchy are essentially simpler because they use modules from the lower levels.

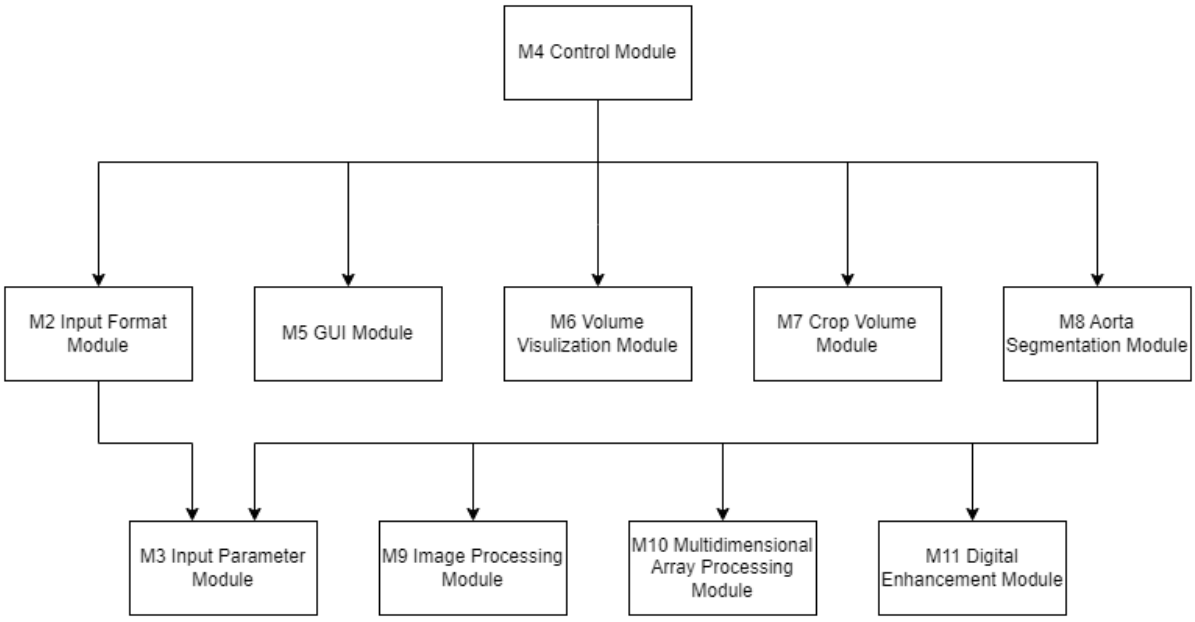


Figure 1: Use hierarchy among modules

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