Fusion of CTA and XA data using 3D centerline registration to aid coronary intervention

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Abstract

Coronary Artery Disease (CAD) is one of the most commonly occurring heart diseases worldwide. It results from the buildup of plaque below the intima layer inside the vessel wall of the coronary arteries. This obstruction in the vessel walls hinders the blood flow to the heart muscle. Furthermore, the rupture of plaque might cause blood clot formation resulting into obstruction of the blood flow leading to heart attack.

The most commonly used treatment techniques for CAD is Percutaneous Coronary Intervention (PCI). It involves introduction of a guide wire through the groin which is moved towards the ostium of the coronary artery. Once the guide wire is in place, a balloon at the tip of the guide wire is inflated at the lesion area which helps open up the vessel. The image guidance of the guide wire is usually done using intraoperative X-ray images which gives the cardiologist a fair idea of the position of the guide wire and the vessel. Though this process yields a good success rate in less complicated occlusions, it is still difficult to obtain good results for complex vascular anatomies, bifurcating lesions and chronically totally occluded vessels. X-ray angiography (XA) only visualizes the lumen of the vessels and suffers from problems like vessel overlap and foreshortening due to the projection nature of the modality. 3D reconstruction of the vessel using 2 projection planes can overcome these problems but the lack of plaque visibility still remains.

In order to circumvent this problem, preoperative coronary Computed Tomography Angiography (CTA) images may be combined with intraoperative X-ray images. CTA gives valuable information about not only the lumen but also the plaque in the coronary vessels which is not visible on the X-ray images. This additional information can help the cardiologist to decide on the best strategy during the intervention. To easily present this information (plaque and lumen) from CTA along with the X-ray images an alignment or registration between these two data sources is needed.

This project involves registration of 3D centerlines extracted from CTA and XA biplane images. Various point set registration methods are investigated and compared. Next, plaque information extracted from CTA is projected onto XA biplane images using the registration method that yields the best results. Finally, the development of a graphical user interface (GUI) is done in order to automate the registration and visualization process.

Keywords: Coronary Artery, CTA, Plaque, Registration, X-ray,
Index

Abstract 1

1. Introduction 1
   1.1 Coronary Artery Disease 1
   1.2 Percutaneous Coronary Intervention 3
   1.3 X-Ray Angiography 4
   1.4 3D X-Ray Angiography Reconstruction 5
   1.5 Computed Tomography Angiography 5
   1.6 Overview 6

2. Materials and Methods 8
   2.1 Overview 8
   2.2 Subjects 8
   2.3 QAngioXA 3D and QAngio CT RE 9
   2.4 MeVisLab 11
   2.5 Pre-processing datasets 12
   2.6 Registration 14
   2.7 3D to 2D Projection 17
   2.8 Validation Scheme 19

3. Results 22
   3.1 Root MSE Comparison Results 22
   3.2 Registration Results 23
   3.3 Validation Results 24
   3.4 Graphical User Interface 26

4. Discussion 28
   4.1 RMSE Comparison Results 28
   4.2 3D Registration 28
   4.3 Plaque Registration 29
   4.4 Projection 29
   4.5 Validation Scheme 31
   4.6 Graphical User Interface 33

5. Conclusions 34

References II - III
Appendix I IV - X
Appendix II XI - XIX
INTRODUCTION

1.1 Coronary Artery Disease

Coronary arteries supply oxygen rich blood to the heart. The coronary arteries present in the myocardium of the heart are divided into two systems 1) Right Coronary Artery (RCA) and 2) Left Coronary Artery (LCA). Regular flow of blood through the coronary arteries is important to maintain proper functioning of the heart. Following image shows the RCA and LCA along with their subdivisions.

Coronary Artery Disease (CAD) is a leading cause of heart related deaths worldwide. According to World Health Organization (WHO), 17.5 million people died from cardiovascular diseases in 2012. Out of which, an estimated 7.4 million were due to coronary artery disease [1]. In 2014, approximately 648,300 Dutch citizens had coronary artery disease [2].

In CAD, there is a hindrance to the normal flow of blood due to the buildup of plaque. The plaque causes the thickening of the inner lining of the artery. The primary reason for plaque buildup is due to injury in the artery which initiates a response from the smooth muscle cells (SMCs). Connective tissues are formed which thickens the intima. Cholesterol, other fats and
inflammatory cells contribute to the atherosclerotic plaque. In response to injury in the artery, SMCs from the media migrate into the intima layer of the artery. These SMCs divide themselves and make connective tissues. These processes of migration, division and synthesis, which collectively are referred to as buildup, causes thickening of the intima. When cholesterol, other fats and inflammatory cells, such as white blood cells, enter the proliferating, thickened intima, the result is an atherosclerotic plaque.

There are different types of plaque that can be formed in the arteries. Primarily they are divided into two categories:

1. Hard Plaque: Calcium deposit in the arteries is also called hard plaque.
2. Vulnerable Plaque: Fibrous fatty tissues and lipid rich necrotic core falls under this category. This plaque type is unstable and can break into smaller parts, which might get lodged into the smaller vessels causing heart attack or stroke.

Following image shows the buildup of plaque in the coronary arteries.

**Figure 2: Plaque buildup in the coronary arteries (Source: Blausen Gallery 2014, Wikiversity Journal of Medicine)**

Consequences of CAD can be broadly classified into two types [3]:

1. **Short Term:**
   a) Cardiac Arrest: Occurs due to improper supply of blood to the ventricles.
   b) Congestive Heart Failure: Occurs when considerable (> 25 %) cardiac muscle fails to receives adequate amount of blood.
2. **Long Term:**
a) Heart Failure
b) Sudden Cardiac Arrest: Can occur due to ventricular arrhythmias.

Treatment of CAD can be:

1) Percutaneous Coronary Intervention (PCI)
2) Coronary Artery Bypass Surgery
3) Medication

We shall be only considering PCI in our study as we deal with imaging complications associated with PCI.

1.2 Percutaneous Coronary Intervention (PCI)

PCI is a procedure performed by an interventional cardiologist to open up the blocked coronary arteries. A catheter is inserted through the inguinal femoral artery or radial artery and guided to the blocked part of the coronary artery. The tip of the catheter has a balloon on top of which a stent is placed. Once in place, the balloon is inflated and the stent goes into place. This opens up the coronary artery and regains back the normal flow of blood to the heart. The catheter along with the deflated balloon is pulled out of the patient, keeping the stent in place. Figure 3 illustrates this procedure.

Different types of stents can be used for coronary intervention. They are:
1. Drug eluting stent: This is a stent placed into the narrowed coronary arteries that slowly releases a drug to block cell proliferation. This prohibits restenosis.
2. Bare metal stent: This is a stent type without any coating. Usually it's a mesh like tube of thin wire.

![Figure 3: A) Catheter along with balloon and stent at the blockage site B) Inflation of the balloon C) Positioning of the stent and recall of the catheter and balloon (Source: Encyclopedia Britannica, Inc.)](image-url)
1.3 X-ray Angiography (XA)

XA is the imaging technique used for guidance of the catheter during PCI. Contrast agent is injected into the coronary arteries in order for them to be highlighted when X-ray images are acquired. Iodine dye is most commonly used as a contrast agent. There can be a monoplane x-ray acquisition or a biplane x-ray acquisition. In monoplane XA, only a single projection plane is considered for coronary vessel visualization. The vessel cross-section is assumed circular as there is only one projection. In biplane XA, two projection planes i.e. frontal and lateral are used for visualization. 3D Coronary lumen can be reconstructed using the perspective projections. Figure 4 shows an X-ray biplane acquisition system from Siemens.

![Figure 4: Siemens Artis Q x-ray biplane acquisition system](image)

Figure 5 shows an example of a biplane angiogram.

![Figure 5: A) Frontal image B) Lateral image (Source: OLV Ziekenhuis, Aalst, Belgium)](image)
There are several drawbacks of this imaging technique.

1. Radiation risk: As x-rays are known to be harmful to human tissues, XA has a radiation risk associated with it.
2. No plaque information: As the contrast agent flows through the vessel, we can visualize the lumen. Any deviation from the regular flow can indicate stenosis but no information about the type of plaque can be deduced.
3. Foreshortening: The actual diameter and length of the vessel might not correspond to the diameter and lengths visualized in the XA images.
4. Overlapping of arteries: As XA is a 2D imaging modality, 3D vessels can overlap each other in the 2D frame. This can give rise to confusion as to which vessel to target.

### 1.4 3D X-Ray Angiography Reconstruction

3D reconstruction of the coronary vessel can be done by using XA biplane images. Frontal and Lateral projections of the same coronary vessel can be used as two projection planes to aid the 3D reconstruction. Figure 6 shows an example of the 3D reconstructed vessel from the angiograms in Figure 5:

![3D XA reconstruction](image)

**Figure 6: XA 3D Reconstruction of the coronary vessel**

### 1.5 Computed Tomography Angiography (CTA)

CT angiography uses a CT scanner to produce detailed images of both blood vessels and tissues in various parts of the body. An iodine-rich contrast material (dye) is usually injected through a small catheter placed in a vein of the arm. A CT scan is then performed while the contrast flows through the blood vessels to the various organs of the body. Numerous x-ray beams and a set of electronic x-ray detectors rotate around the patient, measuring the amount of radiation being absorbed throughout your body. At the same time, the examination table is moving through the scanner, so that the x-ray beam follows a spiral path. All the data is processed to form multiple 2D images of the region of interest. A typical example of CT images is given below. Combining the various 2D images in a stack produces a 3D volume (figure 7).
Figure 7: a) CT slices of the cardiac region with highlighted coronary artery  b) 3D extracted aorta and coronary centerlines with 3D heart volume rendering.

Advantages of CTA:
1. Full 3D coronary tree: Multiple 2D slices of the cardiac CTA can be combined together to form a 3D coronary tree. This helps greatly in visualization of the coronary arteries.
2. Plaque information: Along with coronary tree information, we also get plaque information from CTA. Differential plaque types such as calcium and vulnerable plaque can be seen in CTA volumes.

1.6 Overview

Our aim of this project is to combine information from XA and CTA in order to aid coronary intervention. As XA is the preferred technique during PCI, we would like to combine CTA information with XA in order to show plaque position and type on XA images. The flow diagram in figure 8 explains this schematically.

Figure 8: Flow chart of the project
We start by extracting coronary 3D centerline information from CTA and XA. Plaque information is available to us from CTA. We register these three components together in the registration phase of the pipeline. After registration the CTA information is projected back onto the original XA images.

The following chapters will explain the datasets that we are going to use for this study including the centerline and plaque extraction methods. This will be followed by the registration methods, back projection methods, error measurement technique and validation method in chapter 2. Chapter 3 will explain the results of our study. This will include 3D registration results, 2D back projection results, error results, validation results and overview of the graphical user interface. In chapter 4 we will discuss our results in detail. We will conclude in chapter 5 by summarizing our entire study.
CHAPTER 2

MATERIALS AND METHODS

This chapter will discuss the datasets used in our study. We will explain the centerline extraction and plaque extraction methods along with the pre-processing required to obtain the point sets for our registration step. We will explain the methodology used to achieve an optimum match between datasets, the projection methods used and the validation steps.

2.1 Overview

![Diagram of workflow](image)

**Figure 9: Overview**

2.2 Subjects

A total of 7 subjects are considered in this study. Our clinical partners in Aalst (Belgium), OLV Ziekenhuis, have provided us with CTA and XA datasets of every subject. CTA might be pre-operative i.e. taken before PCI is performed or post-operative i.e. taken after PCI is performed. Hence, certain datasets will contain stent information that is visible in CTA while other datasets might not contain stent information.
Our target vessel for each case can differ. For certain subjects we will be considering the right coronary artery (RCA) and for other subjects we will be considering the left coronary artery (LCA) or left circumflex artery (LCX). The choice of these vessels is done based on visual quality of the vessels in the datasets. For eg, if the RCA is better visible in subject 5 than the LCA, we will select the RCA for this subject. XA biplane images of each dataset is given in the appendix (figure 27 -33).

2.3 QAngioXA 3D and QAngioCT RE

For centerline, lumen and plaque extraction from XA and CTA datasets, we use the QAngioXA 3D and QAngioCT Research Edition (RE) (Medis imaging system b.v., Leiden, The Netherlands) software respectively.

2.3.1 QAngioXA 3D

An XA biplane acquisition consist of two simultaneous obtained projections, frontal and lateral, of the coronary arteries. The 3D lumen reconstruction from these projections consist of the following steps. First 2D centerlines are detected in the biplane images. A centerline is defined as the curve that passes through the center of the vessel lumen. Wave propagation algorithm [6] is applied which finds a smooth corresponding path which results in the lowest cost between the start and the end position of the lumen. For this, good lumen border detection is required. The QAngioXA 3D system detects the lumen border using a validated contour detection algorithm [4]. It is needed to manually select the start and the end position of the vessel segment of interest in the software.

For 3D reconstruction of the lumen from the two lumen contours we need a relation between the frontal and lateral centerlines. This is facilitated using the epipolar constraint [5]. Based on the corresponding path, point reconstruction is applied based on the correspondence. Point reconstruction algorithm suggested by Dumay and Wahle is adopted [5, 7]. The complete 3D reconstruction process is detailed by Shengxian Tu et al. [8]. A step by step 3D lumen reconstruction is given in the appendix I of this report.

We reconstruct the 3D lumen for each of the 7 datasets. The output of the QAngioXA 3D system provides us with:

1. 3D lumen information for each branch (main and side)
2. Diameter information of lumen for each branch.
3. Geometry information of the 3D reconstruction system that includes, image aspect ratio, pixel size information, source to detector distance and offset correction terms. This information will be used for back projection of registered centerlines and plaque onto frontal/lateral images.
2.3.2 QAngio CT Research Edition (RE)

Coronary CTA allows to image the coronary arteries in 3D. The QAngio CT software uses a vesselsness filter to extract the centerlines of the complete coronary tree including main and side coronary branches [9].

For selected vessels in the extracted coronary tree a validated contour detection scheme is applied to detect the lumen and vessel wall contours. Based on the lumen and vessel contours the plaque region in between is analyzed to classify different plaque types [10].

The centerline and lumen information from each vessel is combined into a single subdivision surface. A subdivision surface presents a smooth surface by iteratively subdividing a coarser piecewise linear polygon meshes. This obtained surface mesh also contains hierarchical information along with centerline and lumen information [11]. Figure 10 shows a smooth surface of the CTA lumen for subject 1. The color coding represents the hierarchal information of the vessels.

Figure 10: Hierarchal information color coded in CTA lumen
Red: Parent Branch; Blue: Bifurcation segment; Green: Child Branch
The step by step procedure of extracting coronary vessels and plaque from QAngioCT software is given in the appendix II.

2.4 MeVisLab

MeVisLab (MeVis Medical Solutions AG Bremen, Germany) is a graphical modular programming environment used for medical image processing and scientific visualization. It supports modules that can perform image registration, segmentation and visualization tasks. Custom modules can be furthermore be constructed using C++ or Python programming languages. Multiple modules can be organized into networks to construct complex data processing and visualization pipe lines. For our study we also integrating the MATLAB programming system with MeVisLab for our registration coding. We will be using the visualization and custom build vessel analyses modules from MeVisLab. Figure 11 shows an example network in MeVisLab.

![Figure 11: MeVisLab Network](image)
2.5 Pre-processing Datasets

Once we have the extracted lumen and plaque information from the QAngio XA 3D and QAngio CT software, we use them as input to the MeVisLab environment. The following pre-processing steps are involved in obtaining centerlines (as point sets) from our datasets:

2.5.1 XA

1. Lumen information for the side branch and main branch is available to us from the QAngio XA 3D system. This consists of both diameter information and 3D centerline position information for each branch.
2. In order to classify the bifurcating centerlines as parent or child and to identify the bifurcation point, we use a branch hierarchy analysis as suggested by Antiga et al. [12]. Each centerline is treated as a hierarchal tree with each branch having a parent branch and child branches. Each centerline (parent or child) is identified by its diameter information. The position of the bifurcation point is governed by the radii of the associated branches.
3. In our study, we have considered one main branch and one side branch. Thus, the centerline extraction method described in the above step will establish three branches, one parent- and two child branches.
4. The centerline information is available as point sets that can used for further processing.

The MeVisLab implementation for this step is given in appendix VI of this report.

2.5.2 CTA

From the obtained 3D lumen surface model created by the QAngio CT software we can easily obtain the same hierarchical centerline information with associated radii for further processing. The MeVisLab implementation of this step is given in appendix VII of this report.

2.5.3 Plaque

Next to the luminal information it is possible to obtain plaque information from the CTA scans. We extract three plaque components from CTA.

1. Dense calcium \(\rightarrow\) Hard Plaque
2. Necrotic Core \(\rightarrow\) Soft Plaque
3. Fibrous Fatty Tissue \(\rightarrow\) Soft Plaque

The above classification of plaque is done in QAngio CT. We use the adaptive threshold method to extract out the plaque components. This method is based on the principle
that plaque attenuation values are influenced by luminal contrast densities [9]. The plaque components are available to us from the QAngioCT system as label images. In order to convert this image data to surface data, we use marching cubes algorithm to generate the mesh. This method extracts the polygon mesh from an image iso surface [13]. This surface information contains vertices that can be modelled as point sets and used for further processing. The MeVisLab implementation of extracting surface mesh data from image iso surfaces is given in the appendix VIII.

Now we have our datasets ready to be registered. Figure 12 shows the XA and CTA point sets along with the plaque components for each dataset. This information will be given as input to the registration module in the MeVisLab environment.

![Figure 12: XA/CTA centerlines and plaque](image-url)
2.6 Centerline Registration

The coronary centerlines extracted from XA and CTA are modelled as point sets. This modelling helps us in using point set registration algorithms for our matching purposes. Our goal is to align CTA information (centerline and plaque) with the XA centerlines.

There are five registration methods being employed on each dataset.
1. Coherent Point Drift (CPD)
2. Diameter CPD
3. Weighted CPD
4. Iterative Closest Point Algorithm
5. Gaussian Mixture Modelling

Each method will be briefly discussed in the following sections.

2.6.1 Coherent Point Drift

Coherent Point Drift [14] is an affine registration algorithm that rotates and translates the moving point set to match the reference (fixed) point set. It constructs the moving dataset (CTA in our case) as a mixture of Gaussians and the fixed dataset (XA in our case) remains as a set of points. Following steps explain CPD:

a) Moving dataset is constructed as a Gaussian mixture model considering each point in the dataset as its own centroid and assuming equal covariance. The reference dataset is untouched i.e. it remains as a set of data points.

b) Correspondence is obtained by maximizing Gaussian mixture posterior probability for a given point in the reference dataset.

c) Expectation-Maximization method is used to obtain the optimum transformation parameters.

d) Expectation step constructs an upper bound of the log likelihood function as shown in equation 1.

\[
E(\theta, \sigma^2) = - \sum_{n=1}^{N} \log \sum_{m=1}^{M+1} P(m)p(x|m) \\
\]

\[\theta = \text{transformation parameters} \]
\[P(m) = \text{prior probability of the reference dataset} \]
\[p(x|m) = \text{posterior probability of the GMM given a point (x) in the reference dataset (m)} \]
\[N = \text{total number of points in the moving dataset} \]
\[M = \text{total number of points in the reference dataset} \]

\[
E(\theta, \sigma^2) = \sum_{n=1}^{N} \log \sum_{m=1}^{M+1} P(m)p(x|m) \\
\]

\[\theta = \text{transformation parameters} \]
\[P(m) = \text{prior probability of the reference dataset} \]
\[p(x|m) = \text{posterior probability of the GMM given a point (x) in the reference dataset (m)} \]
\[N = \text{total number of points in the moving dataset} \]
\[M = \text{total number of points in the reference dataset} \]

e) Maximization step minimizes the negative log likelihood function which in turn maximizes the posterior probability hence leading to optimum correspondence.
CPD is an effective registration method to combine CTA and XA centerlines. Following are the advantages and disadvantages of CPD.

**Advantages:**
1. Coherent movement of the Gaussian centroids maintains the shape of the centerline. This is especially beneficial for plaque projection.
2. Compensates for noise and outliers.

**Disadvantages:**
1. No prior information is incorporated into the registration algorithm. All the Gaussians are given equal weights which might not be suitable for every dataset.

We can overcome this drawback by introducing certain modifications to the CPD method. We can add additional available information such as diameter and landmark information to make CPD more robust. Following two sections explain this.

### 2.6.2 Diameter Coherent Point Drift

The centerline information for CTA and XA is extracted from 3D tubular structures. Each point in the centerline has an associated tubular diameter. Ideally, matching points in the datasets should have the same diameter. Hence, diameter parameter is good prior information that can increase the robustness of CPD. Following steps briefly explain the process:

**a)** Construct the Gaussian mixture model of the moving dataset by considering position and diameter information at each point in the dataset as shown in equation 2.

\[
p = [p_x \ p_y \ p_z \ D]
\]

\( p_x, p_y, p_z = \text{position information of each point in the dataset} \)
\( D = \text{diameter information of each point in the dataset} \)

**b)** Repeat the optimization scheme using EM algorithm given in steps c) – e) of section 2.6.1.

### 2.6.3 Landmark Guided Coherent Point Drift

The bifurcation point is the point on the centerline where the side branch joins the main branch. This point is known to us for both the CTA and XA datasets. Thus, we can use this as landmark point to guide our registration. Following steps explain this process:

**a)** Giving a higher weight to the landmark point helps the registration anchor both the
datasets at this point.

b) We give a weight factor of 200 to the landmark point in the moving and the fixed dataset.
c) Construct the Gaussian mixture using the weighted centerline. This will increase the weight of the Gaussian at the landmark point.
d) Repeat the optimization scheme using EM algorithm given in steps c) – e) of section 2.6.1.

2.6.4 Iterative Closest Point Algorithm

ICP is the most common rigid point set registration algorithm present in literature. It uses a simple distance metric to match two point sets, one of which is a moving dataset and the other, a fixed dataset. In this iterative scheme, points between both the datasets are associated with each other in every step based on the distance between them. Singular value decomposition is used to minimize the distance error metric and compute the translation and rotation matrices [15].

2.6.5 Gaussian Mixture Modelling

GMM is a registration method to match point sets. It constructs each point set as a mixture of Gaussians and then applies a distance metric to minimize the distance between them. The distance metric used is given by equation 3.

\[
d(S, M, \theta) = \int (gmm(S) - gmm(M\theta))^2 dx \tag{3}
\]

\[
gmm(S) = \text{Gaussian mixture model of the reference dataset}
\]

\[
gmm(M\theta) = \text{Gaussian mixture model of the moving dataset}
\]

\[
\theta = \text{transformation parameters}
\]

Minimization of the above distance metric yields rotation, translation and scaling parameters [16].

2.6.6 Registration output

All of our 7 datasets go through each of the above 5 registration algorithms. The output of each registration is a translation and rotation matrix which can be applied to the original CTA data to align it with the 3D information obtained from the QAngio XA 3D system.

2.6.7 Registration Error

For each method the root mean squared error (RMSE) between the 3D registered centerlines can be computed. The following steps explain this process:

a) Calculate the closest point in the registered CTA centerline for each point in the XA
centerline. This is because we usually have larger CTA centerline than an XA centerline. Thus we do not consider CTA points beyond the length of the XA centerline. K nearest neighbor (KNN) closest point algorithm [17] is selected for this step.

b) Between the set of closest points we calculate the Root Mean Squared Error given in equation 4.

\[
MSE = \frac{1}{n} \sum_{i=1}^{n} (Y_i - X_i)^2 
\]  \hspace{1cm} (4)

\[n = \text{total number of points in the XA centerline}
\]
\[Y = \text{XA dataset; } X = \text{CTA dataset}
\]

2.6.8 Plaque Registration

Each plaque iso surface contains vertices that denotes the 3D position information for each kind of plaque. This position information can be combined with the rotation and translation matrices we get from the registration of CTA and XA centerlines.

The MeVisLab implementation of the registration methods is given in the appendix IX.

Next sections will focus on the projection of our 3D registration onto XA biplane images and the validation scheme followed to assess the registration.

2.7 3D to 2D Projection

To visualize the CTA information on the XA images, the 3D registered centerlines and plaque have to be projected onto the 2D XA biplane images. We have implemented two projection methods, one of which depends on the geometry parameters of the XA system and the other depends on the 3D to 2D correspondence table available to us from the QAngioXA software.

2.7.1 Perspective Projection

Projection of 3D coordinates to a 2D plane requires the construction of a perspective projection matrix. The information of the x-ray optics geometry is stored in the DICOM images and is available to us from the QAngioXA 3D system. Figure 13 illustrates the projection problem:
The vectors in the image show the direction of projection. The focal position is available to us along with distance between the focus and the detector. Also the distance between the focal point and the angiographic iso center is provided in the DICOM information. We can also calculate the direction of projection using the information available to us. Next, we follow the approach used in 3D rendering in computer graphics. Each 3D coordinate is transformed to the 2D projection plane by projecting the point to a cube. The dimensions of the cube can be calculated using the pixel size and aspect ratio of the biplane images. The pipeline in figure 14 is used to achieve projection onto plane coordinates:

The object coordinates have to be transformed to eye coordinates using a model view matrix. The object coordinates correspond to the 3D centerline coordinates we have. The perspective projection matrix transforms the eye coordinates to clip coordinates. This coordinate system defines the viewing space in which the projection plane lies. Homogenous coordinates are considered i.e. X, Y, Z, W. The fourth coordinate is used for normalization [19]. This parameter is governed by the pixel size and aspect ratio. Finally, a translation and scaling operation is performed to fit the coordinates to the projection plane [20].
2.7.2 3D to 2D Correspondence Table

The QAngio XA 3D software reconstructs the 3D XA centerline from the frontal and the lateral images. Thus, each point in 3D has a corresponding point in the 2D images. This relation between 3D and 2D is given in a correspondence table provided by the QAngioXA 3D system.

For 3D to 2D projection of CTA, we follow the following steps (refer figure 15):

a) Project the 3D registered CTA and the 3D XA centerline onto XA biplane images using the perspective projection method. Call these XA_p (Orange centerline) and CTA_p (blue centerline).

b) For each CTA_p calculate the closest XA_p point and compute the vector \( V_p = CTA_p - XA_p \).

c) Based on the original 3D XA point corresponding to the closest XA_p find the real 2D position of XA point from the correspondence table (figure 43 in appendix II). Call this 2D point XA_{2D}.

d) The final projected CTA point is then defined as CTA_{final} = XA_{2D} + V_p.

![Figure 15: Perspective projection of 3D CTA and 3D XA centerlines](image)

Following are the steps to project the plaque vertices from 3D to 2D:

a) Calculate the closest point between each plaque vertex point and 3D XA centerline. Call this P_{XA3D}.

b) Project P_{XA3D} onto the biplane images using perspective projection method. Call this point P_{XA2D}.

c) Calculate the closest point using K-nearest neighbor between P_{XA2D} and the 2D XA centerline points for each biplane image. Call this XA_{2D}.

d) Vector between P_{XA2D} and XA_{2D} is the offset i.e. \( V_p = P_{XA2D} - XA_{2D} \).

e) Project the 3D plaque onto the XA biplane images using perspective projection. Call this point P_{2D}.

f) The final plaque point is given by \( P_{final} = P_{2D} + V_p \).

Both the above given projection methods are suitable for visualizing the centerlines and plaque on the 2D images. MeVisLab implementation of the above projection methods are given in
2.8 Validation Scheme

We now have the 3D registration of centerlines and plaque. Also, we have the 2D projection of this information onto the 2D XA biplane images. In this section, we will describe a validation scheme using artificially created XA images to assess our registration and projection methods. The flow chart in figure 16 illustrates this scheme:

In the above validation scheme, the original 3D CTA (CTA\textsubscript{orig}) centerline is transformed according to the 3D XA (XA\textsubscript{orig}) centerline in order to get CTA into the XA space. Let us call this new 3D centerline as CTA\textsubscript{trans}. This is projected onto the XA images using the perspective projection method. We embed three landmark markers into CTA\textsubscript{trans}. These landmark points are the first point of the CTA centerline, bifurcation point and the last point of the CTA centerline. These markers are projected onto the XA biplane images. These points will help us reduce manual error in reducing offset in the QAngioXA 3D system. Figure 17 shows the artificially generated XA images.
The QAngioXA 3D software is used to reconstruct the artificial 3D XA centerline, let us call this as XA_{arti}. This centerline is registered with the original 3D CTA (CTA_{orig}) centerline to get the 3D CTA into the new XA space. Let us call this transformed CTA centerline as CTA_{new}. We expect CTA_{new} to match CTA_{trans}. The Root Mean square error (RMSE) is computed between each corresponding point in CTA_{new} and CTA_{trans}. Any errors being produced will indicate errors in registration or projection.

For 2D error evaluation, we can project CTA_{new} onto the XA images and compute the 2D MSE between corresponding points in the frontal centerline for artificial projection and original projection. Similarly for lateral projection.
Chapter 3

RESULTS

This chapter will describe the results for our study. We will start with illustrating the 3D registration and 2D projection results of each of our 7 datasets. The MSE error comparison of the different registration algorithms is given. Results from the validation scheme are also described for both the 3D and 2D cases. Finally, we will explain the graphical user interface (GUI) that is developed.

3.1 Root Mean Squared Error (MSE) Comparison Results

We computed the root mean squared error between the registered 3D CTA centerlines and the 3D XA centerlines for the different registration methods. Table 1 gives an overview of the MSE errors. The bar chart in figure 18 gives a graphical representation of the results between the three CPD algorithms, GMM and ICP:

Table 1: Root Mean Squared Error results (table)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Error CPD Original</th>
<th>Error CPD Weighted</th>
<th>Error CPD Diameter</th>
<th>Error GMM</th>
<th>Error ICP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>1.09</td>
<td>1.62</td>
<td>6.46</td>
<td>14.24</td>
</tr>
<tr>
<td>2</td>
<td>0.97</td>
<td>2.16</td>
<td>0.84</td>
<td>1.26</td>
<td>2.79</td>
</tr>
<tr>
<td>3</td>
<td>2.56</td>
<td>2.31</td>
<td>2.33</td>
<td>3.33</td>
<td>8.54</td>
</tr>
<tr>
<td>4</td>
<td>1.49</td>
<td>1.83</td>
<td>1.35</td>
<td>13.76</td>
<td>12.42</td>
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<tr>
<td>5</td>
<td>1.07</td>
<td>1.95</td>
<td>0.99</td>
<td>1.47</td>
<td>2.46</td>
</tr>
<tr>
<td>6</td>
<td>1.45</td>
<td>2.59</td>
<td>1.46</td>
<td>9.22</td>
<td>4.02</td>
</tr>
<tr>
<td>7</td>
<td>1.24</td>
<td>2.44</td>
<td>1.12</td>
<td>6.44</td>
<td>1.53</td>
</tr>
</tbody>
</table>

*errors are in mm

Figure 18: Root Mean Squared Error results (bar chart)
We support the above quantitative results with the following visual results (figure 19). We compare the three registration methods (CPD, GMM and ICP) for three subjects.

Subject 1

Subject 3

Subject 4

CPD  GMM  ICP

Figure 19: 3D Registration comparison between CPD, GMM and ICP

3.2 Registration Results

From table 1 and figure 18 we can deduce the best registration method for each of our 7 subjects. CPD and its modifications yield the least root mean squared error for each subject. Figures 27 - 33 in the appendix section of the report gives the 3D registration and plaque overlay biplane images for each subject using the best registration algorithm according to the least root mean squared error.
3.3 Validation Results

We will describe the results for the validation scheme given in section 2.7 of chapter 2. The 3D and 2D errors are given in the table for each subject followed by a graphical representation of the results. All the errors are in mm unless otherwise mentioned (Pixel). For 2D case we mention the error in mm (RMS) and in pixels. The pixel size assumed for each subject is approximately 0.358 mm.

Following tables and bar graphs illustrate the validation error described in section 2.8 of chapter 3. The error is given for each subject and for each of the 5 registration algorithms.

Table 2: Root Mean Squared Error results for 3D validation scheme

<table>
<thead>
<tr>
<th>Subject</th>
<th>CPD Original</th>
<th>CPD Weighted</th>
<th>CPD Diameter</th>
<th>GMM</th>
<th>ICP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.58</td>
<td>2.19</td>
<td>3.32</td>
<td>45.87</td>
<td>98.32</td>
</tr>
<tr>
<td>2</td>
<td>1.27</td>
<td>31.54</td>
<td>2.95</td>
<td>48.26</td>
<td>6.40</td>
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<tr>
<td>3</td>
<td>24.47</td>
<td>39.00</td>
<td>29.86</td>
<td>69.35</td>
<td>46.72</td>
</tr>
<tr>
<td>4</td>
<td>3.16</td>
<td>4.19</td>
<td>3.04</td>
<td>36.29</td>
<td>27.90</td>
</tr>
<tr>
<td>5</td>
<td>5.33</td>
<td>7.39</td>
<td>4.92</td>
<td>5.82</td>
<td>10.54</td>
</tr>
<tr>
<td>6</td>
<td>3.67</td>
<td>5.98</td>
<td>3.87</td>
<td>56.14</td>
<td>10.26</td>
</tr>
<tr>
<td>7</td>
<td>21.22</td>
<td>21.65</td>
<td>20.92</td>
<td>44.99</td>
<td>68.13</td>
</tr>
</tbody>
</table>

Figure 20: Root Mean Squared Error results for 3D validation scheme
Table 3: Root Mean Squared Error results for 2D validation scheme (pixels)

<table>
<thead>
<tr>
<th>Subject</th>
<th>CPD Original</th>
<th>CPD Weighted</th>
<th>CPD Diameter</th>
<th>GMM</th>
<th>ICP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frontal</td>
<td>Lateral</td>
<td>Frontal</td>
<td>Lateral</td>
<td>Frontal</td>
</tr>
<tr>
<td>1</td>
<td>5.76</td>
<td>3.87</td>
<td>7.56</td>
<td>4.04</td>
<td>9.76</td>
</tr>
<tr>
<td>2</td>
<td>6.46</td>
<td>3.43</td>
<td>131.26</td>
<td>125.15</td>
<td>14.80</td>
</tr>
<tr>
<td>3</td>
<td>116.85</td>
<td>73.45</td>
<td>187.52</td>
<td>105.55</td>
<td>144.02</td>
</tr>
<tr>
<td>4</td>
<td>12.63</td>
<td>15.78</td>
<td>18.97</td>
<td>16.78</td>
<td>12.14</td>
</tr>
<tr>
<td>5</td>
<td>16.28</td>
<td>14.01</td>
<td>19.34</td>
<td>17.29</td>
<td>16.34</td>
</tr>
<tr>
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<td>15.38</td>
<td>13.00</td>
<td>22.39</td>
<td>19.54</td>
<td>15.67</td>
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<tr>
<td>7</td>
<td>40.39</td>
<td>102.78</td>
<td>42.95</td>
<td>100.71</td>
<td>38.96</td>
</tr>
</tbody>
</table>

Table 4: Root Mean Squared Error results for 2D validation scheme (mm)

<table>
<thead>
<tr>
<th>Subject</th>
<th>CPD Original</th>
<th>CPD Weighted</th>
<th>CPD Diameter</th>
<th>GMM</th>
<th>ICP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frontal</td>
<td>Lateral</td>
<td>Frontal</td>
<td>Lateral</td>
<td>Frontal</td>
</tr>
<tr>
<td>1</td>
<td>1.6</td>
<td>1.08</td>
<td>2.11</td>
<td>1.12</td>
<td>2.72</td>
</tr>
<tr>
<td>2</td>
<td>1.8</td>
<td>0.95</td>
<td>36.6</td>
<td>34.9</td>
<td>4.12</td>
</tr>
<tr>
<td>3</td>
<td>32.58</td>
<td>20.48</td>
<td>52.29</td>
<td>29.43</td>
<td>40.16</td>
</tr>
<tr>
<td>4</td>
<td>3.52</td>
<td>4.4</td>
<td>5.29</td>
<td>4.68</td>
<td>3.38</td>
</tr>
<tr>
<td>5</td>
<td>5.82</td>
<td>8.19</td>
<td>6.92</td>
<td>6.18</td>
<td>4.41</td>
</tr>
<tr>
<td>6</td>
<td>5.5</td>
<td>4.57</td>
<td>7.99</td>
<td>6.99</td>
<td>5.6</td>
</tr>
<tr>
<td>7</td>
<td>11.26</td>
<td>28.66</td>
<td>11.97</td>
<td>28.08</td>
<td>10.86</td>
</tr>
</tbody>
</table>

Figure 21: Root Mean Squared Error results for 2D validation scheme (pixels)
3.4 Graphical User Interface

We have combined our registration and visualization setup into a single graphical user interface (GUI). Following image shows the GUI and its functions:
This chapter has described the registration results with corresponding 3D and 2D images. MSE error comparison and validation errors for three registration algorithms have also been detailed along with tables and bar charts. Overview of the GUI has been presented at the end of the chapter.

**Figure 23: Graphical User Interface**

This chapter has described the registration results with corresponding 3D and 2D images. MSE error comparison and validation errors for three registration algorithms have also been detailed along with tables and bar charts. Overview of the GUI has been presented at the end of the chapter.
Chapter 4

Discussion

This chapter will discuss the results of our study. We will describe the significance of the MSE result comparison between the registration algorithms. We will analyze the 3D registration result and 2D projection result of our subjects along with the results of the validation scheme. Finally, use of the graphical user interface is described.

4.1 MSE Results

We have compared our centerline registration results with already present point-set registration algorithms. The results given in figure 18 illustrate the error in mm between nearest corresponding points in the registered CTA and XA centerlines. We observe that CPD and its modifications constantly yield lower error than Gaussian mixture modelling (GMM) or iterative closest point algorithm (ICP). This is because ICP uses a trivial matching criteria for the two datasets. The distance measure is not sufficient enough to match the centerlines. For GMM, we do not consider any prior information such as bifurcation or diameter. Thus, GMM depends solely on position information for construction of Gaussian mixtures. This can produce inaccuracies in the registration. Finally, CPD constructs Gaussian mixtures with diameter or bifurcation information. This prior information helps to match the datasets accurately.

This above inference is supported by visual results shown in figure 19. In ICP, the moving centerline is flipped with respect to the fixed centerline. This is the cause of high RMSE values for ICP based registration. These results show that CPD and its modifications is a better registration approach for our datasets as compared to some of the other registration methods present in literature.

4.2 3D Registration

Our approach towards the subject has introduced 3D point set registration in the field of XA/CTA matching. We performed 3D registration of coronary centerlines through 5 different methods. We compared the RMSE values of each registration for each of our 7 subjects. From this, we conclude that registration using coherent point drift (CPD) and its modifications yields good results quantitatively and visually i.e. the two centerlines align with each other showing proper point by point correspondence. This is supported by the first three bars of each subject in figure 18 which have a lower height than the last two bars for each subject. Figures 27-33 (in the appendix) show the results visually. The proper alignment of the centerlines is required for plaque matching as we use the same transformation criteria for plaque as we use for centerlines. Thus, good centerline registration yields good plaque matching and this seen for CPD based registrations.
As an overview, original CPD results is the best registration for 2 out 7 subjects, the weighted CPD results in the best registration for 1 subject and diameter CPD results is the best registration for 4 out of 7 subjects. The difference in registration between various CPD methods can be attributed to the centerline extraction. Certain datasets have more accurate 3D centerline reconstruction than others owing to the visual quality of XA and CTA datasets. We can approximate the diameter in a better way if the lumen is clearly visible in XA and CTA whereas the bifurcation point can be approximated in a better way if the side and main branch have a clear distinction. Thus, the argument of different subjects yielding better registration through different CPD methods can be answered based on the visual quality of the datasets.

Another important aspect to be noted is seen in subject 3 (Figure 29 in the appendix). Though the registration looks good, we can clearly see that CTA phase does not match with the XA phase. We have taken utmost care in selecting datasets at the same phase but for certain datasets it is difficult to do so owing to the lack of visible lumen at the same phase for both CTA and XA. This forces us to select a different phase for CTA and XA.

**4.3 Plaque registration**

Plaque registration and visualization is new in the field of CTA/XA matching. Previous studies involved 2D registration of XA and CTA coronary centerlines with very little mention about plaque. Hye-Ryun Kim et al. [21] match XA and CTA data using robust point matching registration algorithm. 2D registration is implemented on centerlines and projection images are obtained. No mention about stenosis or type of plaque is given. Nora Baka et al. [22] implements a modification of GMM, oriented GMM, to match XA and CTA data. This study also does not talk about stenosis or plaque. Gerardo Dibildox et al. [23] use oriented and weighted GMM to register XA and CTA 3D centerlines. This study matches our approach of 3D registration but gives no mention about plaque. Our plaque visualization scheme is new in this field.

**4.4 Projection**

The 3D information (registered centerlines and plaque) is projected onto the XA biplane images. Two methods of projection are explained in chapter 2. Each method has its advantages and drawbacks. As a guide, if projection of plaque information is not of importance, projection using correspondence table is preferred as this method gives a direct relationship between 3D and 2D points. Whereas, if plaque projection is of interest, perspective projection is preferred with certain correction routines implemented using correspondence table.

The perspective projection method is the chosen method for our results (Figures 27 – 33 in the appendix). For subjects 4, 5 and 6, there is a visible offset between the projected information and the actual lumen visible in the frontal image of their respective subject. This offset is not seen for lateral images. Figure 24 illustrates this for subject 4.
The above problem arises because the perspective projection method uses the geometrical properties available from the QAngioXA software. These properties include offset measures computed during centerline extraction and 3D reconstruction. On 3D reconstruction of XA centerline, the QAngioXA system has a bias towards the lateral projection thus a compromise is found between lateral and frontal projection. This compromise can result in a non-matching frontal projection. We also observe that different length segments can create a problem of imperfect matching when projecting from 3D to 2D. This can be seen for subject 4 (Figure 30 in the appendix) and subject 7 (Figure 33 in the appendix).

The above problem can be overcome by using the correspondence tables available to us from the QAngioXA system. This one to one correlation between the 3D points and 2D points, gives us an accurate 2D position for every 3D point. The drawback of this method is that we have to approximate the plaque position using the perspective projection method which might lead to errors. As a consequence of these above drawbacks, we need to find a compromise between accurate centerline projection and plaque projection. Thus choosing the projection method can depend on the desired output of the projection.

Figure 25 shows the frontal XA images for three subjects with the projection comparison using correspondence table and perspective projection method:
In conclusion, projection of the centerlines and plaque leads to visualizing the calcium, necrotic core and fibrous fatty tissues on the XA biplane images. As previously mentioned, XA does not originally yield much information about plaque and thus this visualization helps in providing important information to the cardiologist about the position and type of plaque. For cases in which we have post-operative CTA (subject 1 and subject 4), the position of the stent and other plaque components can be clearly seen in the frontal/lateral projection. These views can be analyzed to observe the movement of the stent or any buildup of plaque post PCI. For cases in which we have pre-operative CTA (subject 2, 3, 5, 6 and 7), cardiologists can localize the position of the plaque in the XA images. This helps in planning the PCI by improving catheter guidance and reduces radiation load on the patient. Previously, CTA and XA scans are compared separately by specialists and plaque position is manually located on the XA images. We have automated the procedure of combining the two scans and providing the precise location of the plaque on XA images.

4.5 Validation Scheme

Once we have our results, we need to validate them in order to assess the results quantitatively. The validation scheme is described in figure 16.

In our centerline extraction stages, there are a lot of manual steps that have to be done. For eg,
in XA, the end and the start position of the centerline has to be selected by the user. Also, the lumen and centerline can be adjusted manually before 3D reconstruction occurs. There can be a difference in the cardiac phase between XA and CTA. This manual interference can create errors in the registration and projection. In order to reduce any manual errors in our registration scheme, we propose the validation scheme.

We create artificial XA images using transformed CTA lumen. Three markers are embedded in the images (figure 17) that guide us in offset selection phase of centerline extraction. This reduces any inaccuracies by the user in selecting points manually. The contrast helps in detecting the lumen accurately. The 3D reconstruction from the artificially generated images (figure 17) is at the exact same phase as the CTA. Thus any errors due to modality difference or phase difference is not there. We register the 3D reconstructed artificial XA lumen with the original CTA and the result is a transformed CTA which ideally should be in the same space as the CTA from which the artificial images were created. The errors mentioned in the above chapter indicate any errors in the reconstruction (3D) or projection (2D).

We calculate the RMSE between each corresponding point in the transformed CTA and the CTA from which the artificial images were created (Table 2 and Figure 20). We observe that there are significant errors in the 3D space between the above centerlines. This is because, QAngioXA system has the freedom to place the 3D reconstructed lumen within a space of certain dimensions. This space is not fixed and can change with different iterations of the reconstruction. Thus, ideally we were expecting the MSE to be negligible as the centerlines should be in the same space, we observe that there is an offset between the two centerlines. This is shown in the figure 26.

The above set of images shows the 3D projection errors for subject 7. CPD yields a good registration and hence the corresponding points yield less MSE as compared to GMM or ICP in...
which the corresponding points are not registered properly.

When we project these 3D projections to 2D XA space, the errors are still significant (Table 3, 4 and Figure 21, 22). This is because 3D to 2D projection is governed by geometric parameters of the QAngioXA system. As discussed before, the QAngioXA system can define its own space to place the 3D reconstruction with respect to biplane images. Ideally we’ll expect the artificial images to match the 2D projection of the transformed CTA, but as projection depends on these geometric parameter we get significant errors.

Projection and reconstruction errors can contribute significantly to the results. In order to limit these errors, accurate 3D reconstruction should be done that involves meticulous steps while extracting centerlines from QAngioXA 3D system. Tweaking the geometric parameters used for projection can also yield better results but this has to be done manually.

4.6 Graphical User Interface

The graphical user interface (figure 23) is an interface tool developed to ease the process of visualizing the 3D registration and projection results. The MeVisLab network that implements our registration and visualization methodology is an extensive network with multiple inputs and outputs. Through the GUI we can load in the XA/CTA datasets and the processing occurs in the background to give us the final result. The average time of registration is approximately 30 seconds.

We aim to combine the GUI with our previous GUI developed during a previous project [18]. The latter GUI combines different point set registration algorithms to give a comparative study between them. Point wise matching is set up between registered centerlines to localize points between CTA and XA centerlines. The point set registration algorithms compared are GMM, ICP and Curvature Signature Technique [14]. This combined GUI is envisaged to be done in the near future.
CHAPTER 5

CONCLUSION

This study has focused on combining XA and CTA information using various registration algorithms. We analyzed five different registration algorithms and compared them qualitatively and quantitatively. Coherent Point Drift (CPD) and its modifications yield the best results and hence they were used for combining the CTA data with XA data during our study. Registered plaque and coronary centerlines are projected back onto the XA biplane images. This visualization provides an enhanced view of the coronary arteries to the cardiologist, which can aid treatment planning for percutaneous coronary intervention. We have developed a graphical user interface (GUI) to automate the registration and visualization process.

Our approach towards plaque registration and visualization is new in the field of CTA/XA matching. Previous studies [21 -23] do not mention about plaque visualization or registration in their implementation. Distinguishing different plaque types and color coding them for visualization purposes is unique to our study.

The work in this area is constantly progressing. There are multiple registration algorithms present that can yield similar or better results. Visualization of plaque can be improved by determining if the plaque is behind the vessel or in front of the vessel while viewing biplane images. We consider a single cardiac phase in our study. We can extend our approach to the entire cardiac cycle. Real time matching of CTA information with XA during PCI can also be achieved in the future.

This study is a start towards achieving better treatment planning for PCI and we envisage a higher quality of work in this area.
REFERENCES


[19]. Coordinate transformation: [http://www.songho.ca/opengl/gl_transform](http://www.songho.ca/opengl/gl_transform)


[23]. Gerardo Dibildox et al., **3D/3D registration of coronary CTA and biplane XA reconstructions for improved image guidance.** *Medical Physics,* 2014; 41:919-925.
APPENDIX I
RESULTS

Subject 1

Figure 27: a) 3D Registration  b) Frontal Projection  c) Lateral Projection
Subject 2

Centerline Projection - Blue: CTA centerline; Orange: XA centerline
Plaque Projection - Grey: Stent; Red: Necrotic Core; Green: Fibrous fatty tissue

Figure 28: a) 3D Registration b) Frontal Projection c) Lateral Projection
Subject 3

Figure 29: a) 3D Registration b) Frontal Projection c) Lateral Projection

Centerline Projection - Blue: CTA centerline; Orange: XA centerline

Plaque Projection - Grey: Stent; Red: Necrotic Core; Green: Fibrous fatty tissue
Subject 4

Centerline Projection - Blue: CTA centerline; Orange: XA centerline
Plaque Projection - Grey: Stent; Red: Necrotic Core; Green: Fibrous fatty tissue

Figure 30: a) 3D Registration b) Frontal Projection c) Lateral Projection
Subject 5

Figure 31: a) 3D Registration b) Frontal Projection c) Lateral Projection

Centerline Projection - Blue: CTA centerline; Orange: XA centerline
Plaque Projection - Grey: Stent; Red: Necrotic Core; Green: Fibrous fatty tissue
Subject 6

Centerline Projection - Blue: CTA centerline;
Orange: XA centerline
Plaque Projection - Grey: Stent ; Red: Necrotic Core ; Green: Fibrous fatty tissue

Figure 32: a) 3D Registration b) Frontal Projection c) Lateral Projection
Subject 7

Figure 33: a) 3D Registration b) Frontal Projection c) Lateral Projection

Centerline Projection - Blue: CTA centerline; Orange: XA centerline
Plaque Projection - Grey: Stent; Red: Necrotic Core; Green: Fibrous fatty tissue
APPENDIX II
DATA PRE-PROCESSING ROUTINE

I. Extraction of 3D coronary centerline from QAngioXA 3D system

Following images show the step by step process for extracting 3D centerline and lumen information from XA using QAngioXA system.

Step 1: Select the cardiac phase for frontal and lateral projection

Step 2: Correct for offset by selecting a landmark point on the two projections
Step 3: Select markers on the projections indicating the start and end of the vessel.

Step 4: QAngioXA system will detect contour of the vessel.

Step 5: 3D reconstruction of the lumen.

Figure 34: Steps for centerline extraction from QAngioXA 3D system.
II. Extraction 3D coronary centerline and plaque from QAngio CT RE system

Following images show the step by step process for extracting 3D centerline and plaque information from CTA using QAngio CT RE system.

Step 1: Coronary vessel tree is reconstructed from the CT slices

Step 2: On selecting the vessel to be investigated, we proceed to the refinement stage
Step 3: This step allows us to manually correct the lumen contours

Step 4: Vessel wall and plaque can be visualized in this step

Step 5: We can combine multiple vessels in this step

Figure 35: Steps for centerline and plaque extraction from QAngio CT RE system
III. Modules Overview

Each module in the network performs a specific task of either processing or visualization. Any input given to a MeVisLab module must either be an X Marker List (XML), Winged Edge Mesh (WEM) or an image input. Matrix inputs can be given as XML. It is a structure that consists of three classes.

1. **Pos**: Position information of the XML is stored in the pos class. For eg. If “test” is an XML, test.pos can be accessed as its position information.
2. **Vec**: This stores the vector information associated with each position point in the XML. For eg, test.vec
3. **Type**: Each point in the XML list has an associated type information. This is an integer differentiating between different set of points in the same XML. For eg, test.type.

WEM is usually used for describing 3D structures. It also consists of three subclasses:

1. **Vertices**: This denotes the 3D position information in the WEM. For eg, if “test” is a WEM, its vertices can be accessed by test.vertices.
2. **Faces**: A 3D structure will have faces that are formed by joining vertices. The faces class denotes this. For eg, test.faces
3. **Edges**: This denotes the edges of the 3D mesh formed by joining the vertices.

IV. Visualization Modules

Following are the visualization modules available to us in the MeVisLab environment.

- **So3DMarkerEditor**: This module helps decide the shape, type, colour and size of the 3D XM list
- **SoView2DMarkerEditor**: This module helps decide the shape, type, colour and size of the 2D XM list
- **SoWEMRenderer**: This module renders a 3D WEM into space
- **SoExaminerViewer**: This module visualizes the output of from the marker editors and the WEM

Figure 36: Visualization modules
V. MATLAB Script Wrapper

We integrate MATLAB (Mathworks Inc.) with MeVisLab using the MATLAB Script Wrapper. Our registration, back projection and validation code is written in MATLAB using the script wrapper.

The script wrapper can take X-marker lists as input. This can be given using the “input base names”. Matrices and scalars can also be given as inputs to the script wrapper. XML, WEM or curve lists can be given as output from the script wrapper.

VI. Extraction of XA centerline point sets

The lumen extracted from the QAngioXA software is available to us for main branch and side branch segments. This includes centerline information and diameter information for each segment. This can loaded into the “ProcessAngio” modules and the centerline point sets can be extracted. We combine the point sets for main branch and side branch using the “MergeLists” module. Each segment is given a different type using the “vmtkCenterlineBranchExtractor” module. We filter the point sets for any outliers and feed it to the “ExtractBifurcationPoint_XA” module. This will give us the bifurcation point for the centerline.

Figure 37: Script Wrapper Interface

Figure 38: XA centerline extraction network
VII. Extraction of CTA centerline point sets

We get the CTA surface from QAngioCT software. This acts as the input to the “WemToSubDivMeshData” module that converts the WEM data to mesh data. “vmtkSurfaceToCenterlines” module extracts the centerlines from the mesh data that is further fed to the “vmtkCenterlineBranchExtractor” module to give each centerline segment a different type. Bifurcation points are extracted using the “ExtractBifurcationPoints_CTA” module.

VIII. Extraction of plaque point sets

Each of the plaque components is modelled as a WEM. This modelling procedure is illustrated in the figure below:

The plaque information from QAngioCT software is available to us as image data. We convert this image data to mesh data using “mLkebSparseImageSurface” module. This mesh is then converted into WEM data using “mLkebMeshToWEM” module. The WEM data can be processed using “MATLAB script wrapper” module.
IX. Plaque Registration

Let rotation matrix from the registration algorithm be given by B and translation matrix be given by T. The transformation of plaque is given by.

\[ \text{Transformed Plaque} = \text{Plaque} \ast B' + T \]

Plaque is a matrix of Nx3 size, where N is the total number of vertices in the plaque component. B’ signifies transpose of the rotation matrix in order to aid multiplication. This mathematical operation is performed for each plaque component.

X. Registration and visualization process in the MeVisLab environment

Following images illustrate the registration process and visualization process in MeVisLab environment.

The CTA and XA point sets (x-marker lists) are given as input to the “MATLAB script wrapper” module. The plaque componenets are given as WEM entries. This module performs registration using CPD and modifications of CPD as described above. The output of this module is again X-marker lists or WEM that is sent to the “So3DMarkerEditor” or “SoWEMRenderer” module. The results are visualized in the “So ExaminerViewer” module. These 3D registration results for each subject is given in the next chapter.
XI. Back projection routine in the MeVisLab environment

Following image illustrates this process in the MeVisLab environment.

![Diagram of network]

**Figure 42: Back projection using correspondence table**

The above network takes the correspondence table and the frontal/lateral centerline as an input. The “MATLAB Script Wrapper” modules are responsible for relating the 3D points to 2D points. Also, the MATLAB module relates the 3D plaque vertices to 2D plaque vertices as described above.

Following is an example correspondence table for one of the datasets. The first column of the table indicates the lateral entries and the second column indicates the frontal entries. The n\textsuperscript{th} row in the table relates the n\textsuperscript{th} 3D point to its corresponding 2D point in the same row for the frontal and the lateral image. Please note that all the table entries are rounded off to their nearest integer as they represent the indices values of the 2D centerlines. Thus by correlating each 3D point to its 2D counterpart, we can obtain the 3D to 2D match for the XA centerline.

**Figure 43: Correspondence table for 3D to 2D projection**