Software Development for X-Ray Fluoroscopy and MR Image Fusion

by

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Software Development for X-Ray Fluoroscopy and MR Image Fusion

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Abstract

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In interventional radiology, treatment is routinely done under X-Ray Fluoroscopy (XF) using special catheters or needles. XF is a fast modality and allows one to follow the endovascular path with contrast injections and to track devices during the interventions. On the other hand, one of the most important problems in XF imaging is the lack of soft tissue contrast; besides the obvious problem of ionizing radiation. During the intervention, additional soft tissue information could decrease the risk by providing important extra guidance to the surgeon. For instance: in endovascular cardiac interventions, detailed anatomical positions of infarcted segments of the heart could highlight target or weak zones on the myocardial wall.

Main goal of this study is to overcome the lack of soft tissue contrast of XF. To achieve this goal soft tissue information gathered from a priori imaging modality is used. MRI is the best candidate with excellent soft tissue contrast and ability to image any cross section in the scanned volume. On the other hand, MRI has deficient features in temporal resolution when compared to XF, instrument compatibility problems with high magnetic and RF fields and limited patient access because of the shape of the magnet bore. Therefore combination of these two modalities all deficient features could be avoided by complementing each other. Combined usage of XF and MRI requires registration of images from both modalities and a reliable software platform is needed for preclinical and clinical studies. In this work, a new implementation of XFM Suite in Extensible Imaging Platform (XIP) software provides all the tools for X-Ray fused with MRI (XFM) clinical studies performed in X-Ray-MRI suites (XMR) with real-time registration and fusion of images.

Keywords: Image-Guided Theraphy, Interventional Radiology, X-Ray Fused with MRI (XFM), Extensible Imaging Platform, Image Fusion, Image Registration

Özet

X-Işınlı Floroskopi ve MR İmge Füzyon Yazılımı

Girişimsel radyolojide rutin tedavi X-Işınlı Floroskopi (XF) tanısal yöntemi kullanılarak özel kateter ve ekipmanlar eşliğinde yapılmaktadır. Floroskopi hızlı bir görüntüleme tekniğidir. Görüntüleme hızı girişim esnasında yapılan kontrast madde enjeksiyonları ile damar içi yolun görüntülenmesini ve kataterin bu sayede damar içerisinde ilerletilmesi sağlamaktadır. Ancak floroskopi işleminin en önemli problemleri yumuşak doku kontrastının eksikliği ve X ışını kullanımından kaynaklanan radyasyondur. Girişim esnasında doktora sağlanacak yumuşak doku bilgisi operasyonun hayati riskini azaltmak ve doktora kritik kararlar sırasında yönlendirmek açısından önemlidir. Örnek olarak endovasküler girişimlerde ölü doku kesiminin detaylı anatomik pozisyon bilgisi doktora hedef nokta ve kalp duvarındaki ince ve hassas kısımlar hakkında bilgi verebilir.

Bu çalışmanın ana amacı XF görüntüleme tekniğinde eksik olan yumuşak doku kontrastının sağlanmasıdır. Bu yumuşak doku bilgisi girişim öncesi başka bir görüntüleme tekniği kullanılarak alınmaktadır. İkinci görüntüleme tekniği olarak Manyetik Rezonans (MR) görüntüleme tekniği mükemmel yumuşak doku kontrastı sağlaması ve görüntülenen hacim içerisinde herhangi bir açıdan kesit görüntüsü verebilmesi nedeniyle en iyi adaydır. Ancak MR görüntüleme tekniğinin de XF tekniği gibi bazı eksiklikleri vardır. Bunlar; düşük olan zamansal çözünürlük, yüksek radyo frekans ve manyetik alanlara uygun ekipman gereksinimi ve MR cihazının şeklinden kaynaklanan sınırlı hasta erişimi olarak sıralanabilir. İki görüntüleme tekniğindeki eksikliklerin çoğu bütünleşik bir birlikte kullanım ile bertaraf edilebilir. İki görüntüleme tekniğinin birlikte kullanımı iki cihazdan elde edilecek görüntülerin çakıştırmasını gerektirmektedir ve bu işlemin klinik ve klinik öncesi kullanımı için güvenilir bir yazılım desteğine ihtiyaç duyulmaktadır. Bu çalışmada önerilen "XFM Suite" yazılımı ile, X-Işınlı Floroskopi altına MR imge füzyon deneyleri için gereken tüm yazılımsal araçlar sağlanmaktadır.

Anahtar Sözcükler: Görüntü Destekli Tedavi, Girişimsel Radyoloji, X-Işınlı Floroskopi Altına MR İmge Füzyonu, XIP, İmge Füzyonu, İmge Çakıştırma.

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LIST OF SYMBOLS

P	Polynomial Function
$c_{x,x}$	Polynomial Function Coefficient
x_h	XF 2D homogeneous coordinate
x_k	XF 3D coordinate

LIST OF ABBREVIATIONS

CT	Computed Tomography
CTF	Computed Tomography Fluoroscopy
DRR	Digital Reconstructed Radiography
FDA	Federal Drug Administration
FOV	Field of View
II	Image Intensifier
IS	Intensifying Screen
ITK	Insight Segmentation and Registration Toolkit
MRI	Magnetic Resonance Imaging
NCI	National Cancer Institute
NMR	Nuclear Magnetic Resonance
OGL	Open GL
OI	Open Inventor
PET	Positron Emission Tomography
PA	Primary Angle
ROI	Region of Interest
SA	Secondary Angle
SID	Source to Image Distance
VTK	Visualization Toolkit
XIP	Extensible Imaging Platform
XF	X-Ray Fluoroscopy
XFM	X-Ray Fused with MRI
XR	X-Ray Radiography

1. Background

1.1 Image Guided Interventions

In medical interventions, procedures have been developed over the last decade following the improvements in supporting medical imaging techniques. While previous surgical procedures require highly invasive techniques, invasiveness of these procedures decreased dramatically with development of guiding imaging. In addition to lowering the cost of the operation, decreased incision areas reduced patients recovery time; generally speaking patients comfort increased with minimal invasiveness. But minimal incision area requires advanced guiding of physicians during interventions. This guidance can be provided by optically from a camera as it is utilized in laparoscopy or arthroscopy. Alternatively, guidance can be provided by external diagnostic imaging techniques like X-Ray (XR), Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). Interventional practices utilizing diagnostic imaging techniques will be discussed further below.

1.1.1 X-Ray Guided Interventions

After the discovery of X-Rays by Wilhelm Roentgen in 1895 this technique is widely used for medical diagnosis. Even the first use was in a month after seminar paper [13]. With the great penetration properties X-Rays are especially useful in detection of pathologies of the skeletal system. But they are also useful in diagnosis of some soft tissue deceases. Chest X-Ray is used for diagnosis of lung diseases like pneumonia, lung cancer or pulmonary edema; or abdominal X-Ray is used to diagnose intestinal obstruction.

X-Ray Fluoroscopy (XF) is a continuous imaging type of X-Ray imaging. In XF the patient is exposed to the ionizing radiation to obtain real-time moving images of the internal structures. Technically XF uses an X-Ray source and a fluorescent screen between which a patient is placed. XF is a golden standard in catheter-based procedures because of its high temporal resolution (15-30 frames per second) and spatial resolution (1024x1024 pixels covering the field of view). XF can guide the physician in real-time with excellent monitoring of the catheter thorough its path in the arteries. It has been used as a guiding technique in a wide range of minimally invasive procedures like treatment of obstructive coronary artery disease, peripheral artery atherosclerosis and aneurysm. Nevertheless, XF suffers from the lack of soft tissue contrast and the dose absorbed by patient during the procedure because of continuous exposition which contributes to long-term risk of malignancy [8] [14].

1.1.2 CT Guided Interventions

Computed Tomography imaging technique became the golden standard in diagnosis of a wide spectrum diseases such as infarctions, tumors, calcifications, hemorrhages and bone traumas in head area, pulmonary embolism (PE) and aortic dissection in chest area. 3D image reconstruction techniques integrated in CT enables physician to access the cross sections or the volume itself and to visualize optimized set of images for the volume of interest (VOI). Relatively high spatial resolution and high acquisition speed enables CT to be used also in interventional procedures as a guide with 3D information of the anatomic structure around the intervention path. Continuous imaging type of CT is called CT fluoroscopy (CTF).

CTF has several advantages for intervention guidance like spatial resolution cross-section selection ability to visualize the catheter and its path from entry point to the target [15] (Sample CT intervention images are shown in Figure 1.1). Additionally, CTF is widely used for guidance of percutaneous abdominal biopsy procedures and drainage of fluid collections with catheters [1]. Furthermore, CTF is an important guidance technique in thoracic drainage procedure and in tracking of transbronchial needle aspiration [16]. CTF suffers from the same problems like XF; actually, dose of absorbed radiation by patient and radiologist are increased dramatically when compared to XF [17].

1.1.3 MRI Guided Interventions

The first classical experiment on deflection of atomic beams in magnetic field is performed by of Stern and Gerlach. And the role of nuclear magnetism on the deflected beam is identified by Rabi which leads to evolution of Nuclear magnetic resonance (NMR). NMR has a foundation of different amplitude and frequency of emitted radio signals by exciting protons within a strong magnetic field. Analysis of differences in amplitude and frequency of the received signal allows identification of the chemical composition of the target element. Throughout the development period of NMR, it was first used in chemistry and later in biochemistry. While other imaging techniques identify the tissues based on few physical properties of tissues, MR imaging (MRI) has more variables to identify tissues like $T_1$and T_2 relaxation times, flow and spectral shifts. Furthermore these variables can be combined with various pulse sequences and pulse times [18]. And MRI provides excellent tissue contrast. Therefore, it could be a good imaging modality for guiding interventions. Interventional MRI is an active research topic. It has advantages over the conventional X-Ray imaging by eliminating the ionizing radiation therefore any hazardous effect on the patient. In addition, medical staff avoids musculoskeletal injuries because of no protective lead aprons are needed. On the other hand, MRI has restrictions mainly because of the high magnetic field around and limited patient access. There are various studies focusing on configurations for MRI suites specialized in clinical interventions based on the restrictions of MRI [2][8]. Additionally, various techniques are proposed about development of medical devices compatible with high magnetic field and catheter tracking techniques in MRI (Images acquired in MRI intervention are shown in Figure 1.2)[19] [2]. Safety and heating of interventional medical devices is another discussion topic in interventional MRI [20].

In this study we focused on supporting XF guided intervention technique with a priori MR images by real-time fusion of both modalities. For fusion of images coming

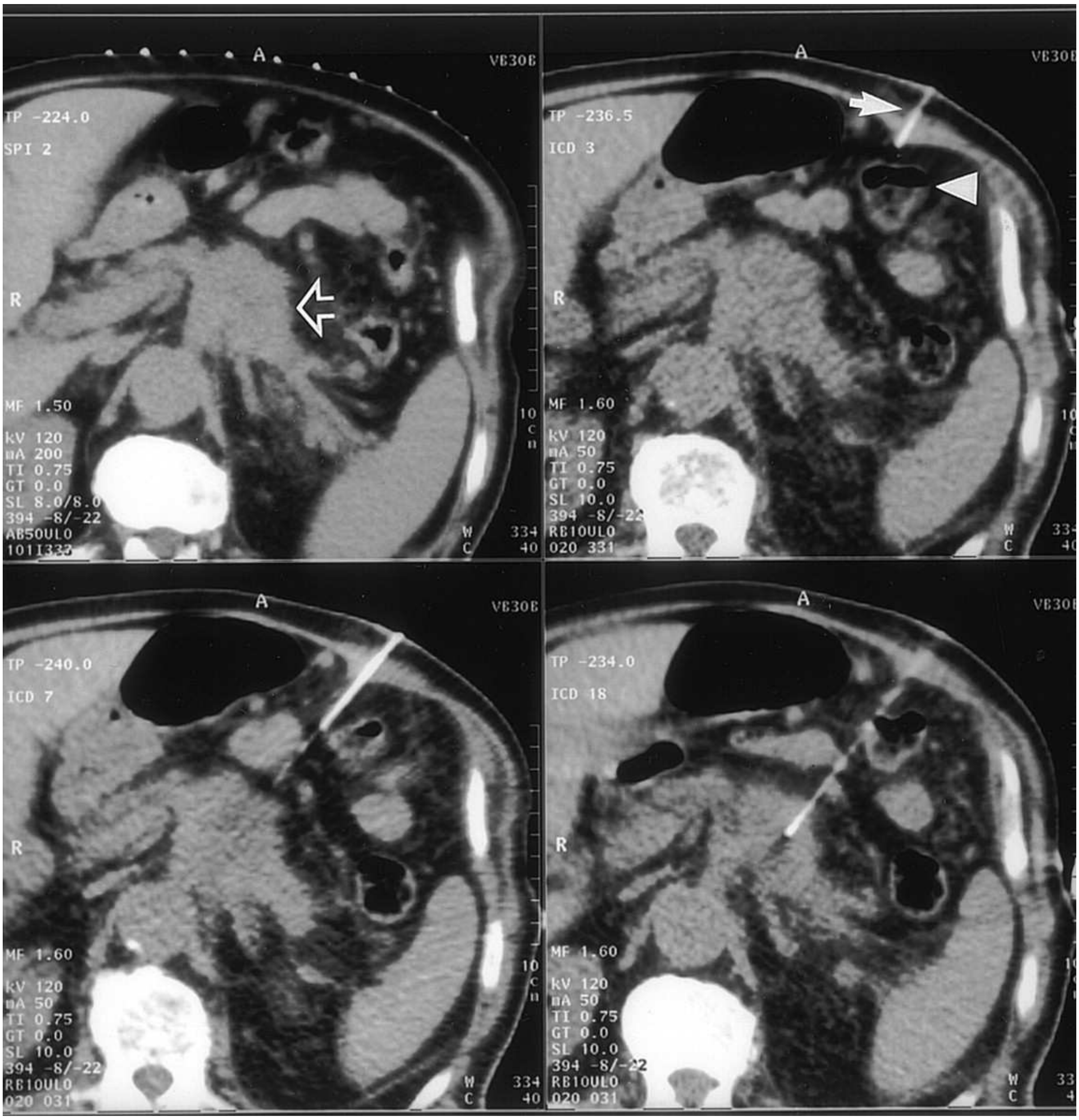

Figure 1.1 Images acquired in CT fluoroscopy-guided biopsy of pancreatic cancer (open arrow) with real-time method. The upper left image shows a bowel-free path to the target. After CT fluoroscopy began , the colon (arrowhead) was between the needle (solid arrow) and the target (seen in upper right image). With CT fluoroscopic guidance, the colon was deflected to the left by the needle placed to the right of the colon (seen in lower left image), guidance allowed the needle to be access the pancreatic mass without piercing the colon (seen in lower right image). (Taken from [1])

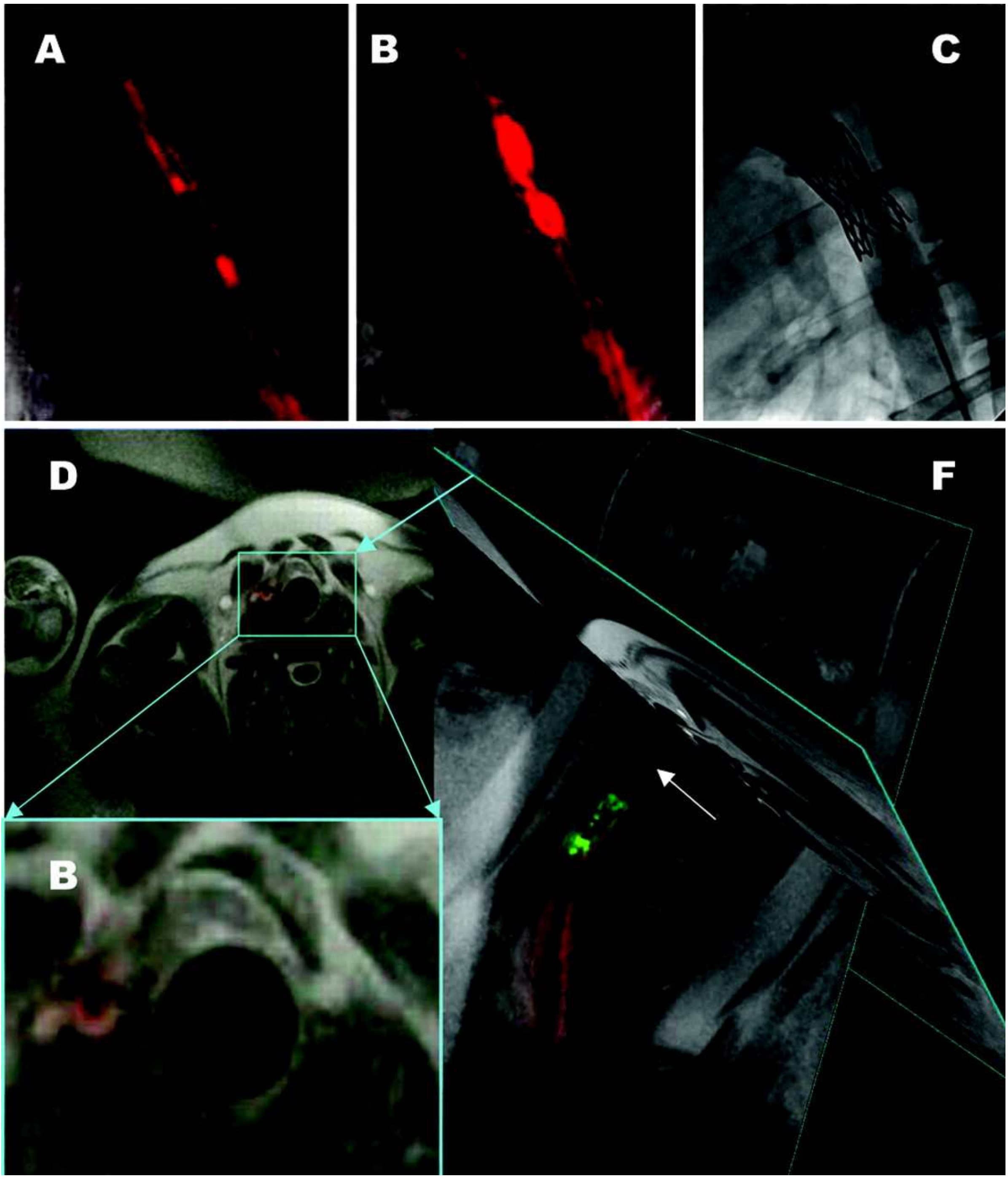

Figure 1.2 Transcatheter procedures under iCMR in "Conventional" (A–C) and "unconventional" (D–F) ways. Stenting in a surgical model of aortic coarctation in swine using both "active" and "passive" catheter techniques are shown in images A–C . A "passive" angioplasty balloon is filled with dilute gadolinium contrast agent and it is used to deliver a "passive" platinum stent with an "active" MRI receiver coil. Various phases of the procedure are shown: A, Stent positioning. B, Stent deployment. C, XRF result. Panels D–F show recanalization of chronic total occlusion of the internal carotid artery. D, Axial localizer. E, Enlarged view shows catheter inside internal carotid artery adventitial borders (red). F, Sagittal view of guiding catheter (green) directs guidewire (red) along trajectory (arrow). (Taken from [2])

from two modalities image registration techniques should be used. An overview of registration techniques is given in the following section.

1.2 Overview of Image Registration Techniques

Image registration can be described as the process of bringing two or more different images of the same scene into a common coordinate system. Possible differences between these images can arise from different imaging times, sensors or viewpoints. The aligned images are named as reference and sensed image. Image registration could be a significant component of image analysis processes which gathers information using a combination of images. Image registration is a typical requirement in remote sensing (environmental monitoring, weather forecasting), computer vision (automatic quality control) and cartography (map updates) [21][22].

Several methods utilized in image registration can be classified based on the criteria formulated by van den Elsen et. al. [23]. A simplified version is presented below based on the version proposed by Maintz et. al [24].

1. Dimensionality

   Images used in registration can be classified by their spatial dimensions or spatial dimensions combined with additional time dimensions. Reference and test image dimensions could be different; examples (relevant to our study) are listed below:

   (a) 2D-2D

   (b) 2D-3D

   (c) 3D-3D

2. Nature of Registration basis

   (a) Extrinsic (based on foreign objects)

      i. Invasive (artificial objects inserted into body of the patient are considered invasive)
      ii. Non-invasive (artificial objects attached to the patient‘s skin are considered non-invasive)
   (b) Intrinsic (based on patient-generated image content)
      i. Landmark-based
      ii. Segmentation-based
      iii. Voxel property based
   (c) Non-image based (calibrated coordinate systems)

   These align the imaging modalities either permanently once, or temporarily when needed.

3. Nature of transformation

   This determines how many parameters we will use for the registration calculations.

   (a) Rigid (only translation and rotation)
   (b) Affine (mapping between parallel lines)
   (c) Projective (mapping lines onto lines)
   (d) Curved (mapping lines onto curves)

4. Domain of transformation

   (a) Local (transformation applies to whole image)
   (b) Global (transformation applies to subsections of the image)

5. Interaction

   (a) Interactive (registration done by the user)
   (b) Semi-interactive (automatic registration with user guidance)
   (c) Automatic

6. Optimization procedure
    (a) Parameters computed (transformation parameters computed directly)
    (b) Parameters searched for (by finding an optimum of a function in parameter space)
7. Modalities involved
    (a) Monomodal (registration of images belong to same modality)
    (b) Multimodal (registration of images belong to different modalities)
    (c) Modality to model (registration of image to a mathematical model)
    (d) Patient to modality (registration of image to patient)
8. Subject
    (a) Intrasubject (images acquired of a single patient)
    (b) Intersubject (images acquired of different patients)
    (c) Atlas (reference image constructed from an image infromation database)
9. Object

    Images used in registration process may have various body-parts as objects, for instance: head, thorax, abdomen, Limbs etc.

Basic information on registration methods utilized or tested in this study or previous studies on XFM procedure software development will be discussed within three major subsections below.

1.2.1 Point Based Registration

Point based registration method is based on matching two point sets with a coordinate transformation. It is accepted as a gold standard because of its robustness and precise matching capability. Point-based registration is the most reliable method in medical imaging with easily identifiable internal or external markers [25][26][27]. Point based registration can be classified depending on the criteria list given in Section 1.2. Dimensionality of registration depends on the number of dimensions of the space in which point sets lie (in our study 3D-3D). Depending on the nature of registration basis point based registration is an extrinsic method with point sets formed by artificial objects attached to subject. Attachment type of objects to the patient categorizes the registration either as invasive, with screw markers; or non-invasive, with skin markers (as employed in our study).

Transformation employed in point based registration is classified as rigid with only translation and rotation components, and as global with application to whole image. Optimization procedure can vary depending on specific usages of the method, for instance in our study automatic registration is employed with only images supplied by user in registration process [24].

Registration error in point based registration is to a large extent independent of the particular object being registered. Therefore with measurements made with phantoms or previous patients, clinical accuracy of the system can be predicted. Yet, there exists error in accuracy of the system with an external component due to error in localization of the markers (fiducial localization error) and an internal error due to marker alignment (fiducial configuration). This highlights our vulnerable nature since we rely on point based registration system and displacement of skin markers after imaging and wrong calibration of the XF system could give us unexpected errors if these are not controlled [28].

1.2.2 Feature Based Registration

Feature-based registration technique depends on matching of various types of features. Process consists of four steps:

- Feature detection: Various types of differentiating objects like regions, line intersections, contours and edges are manually or automatically detected. Reliability of feature detection affects the following steps, therefore this step should be designed with caution.

- Feature matching: Correspondence between the features detected in sensed and reference images is performed. Correspondence map is formed by employing various similarity measures and feature descriptors.
- Transform model estimation: A transformation function is constructed with information of established correspondences.
- Image transformation: Using transformation function formed in previous step sensed image is transformed.

Feature-based registration could suffer from unreliable feature detection algorithms since the whole process is based on the quality of features detected. Feature-based registration differs from point-based registration since it utilizes different types of features used (lines, regions, edges, etc.). Point-based registration could be thought as a special case of feature-based registration where features are points and all matching information between 3D sets is known [22].

1.2.3 Intensity Based Registration

Intensity-based registration is an intrinsic registration method based on only patient-generated image content matching regions with pixel value similarity measures. Correspondence estimation is mainly an iterative process which runs until an error less than a certain threshold is achieved on the chosen similarity based measure. Intensity based registration is a commonly used method in registration of functional MR images with anatomical images and atlas images provided by image database to find functional activity of the brain with anatomical information. Sample intensity based registration results in an fMRI study by Karahan et. al. are shown in Figure 1.3. Registration of X-Ray images with corresponding CT projections, digitally reconstructed radiographs

(DRR), is another application area of intensity based registration. This process requires right orientation of CT volume according to X-Ray instrument parameters to achieve a perfect match with intensity-based registration [29]. Additionally, Durmaz et. al. discussed intensity-based registration approach for XFM studies in his thesis [10].

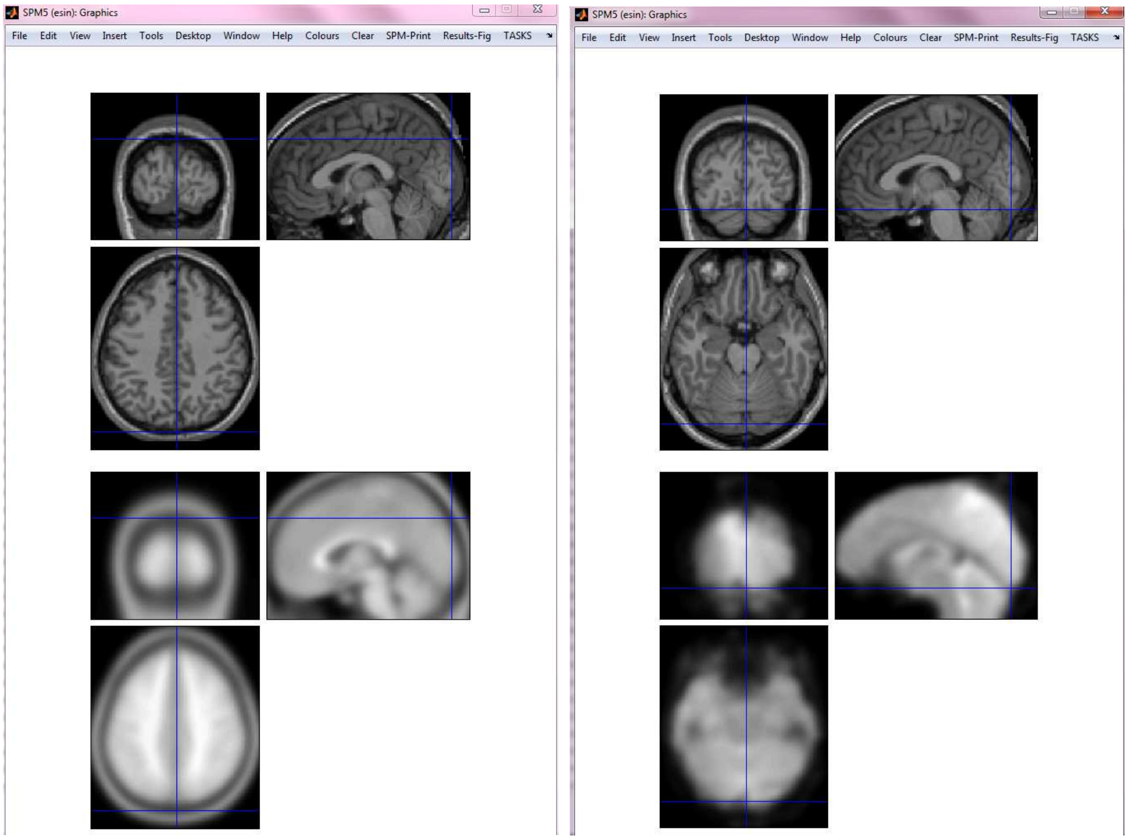

Figure 1.3 Intensity based registration results between anatomical MR images and MNI 152 template (left), anatomical MR images and fMRI images (right). (from [3]).

Major bottle-neck of intensity-based registration is computation time. Iteration process requires many comparisons between sensed and reference images before an optimal match is achieved.

1.3 Image Fusion Techniques in Medical Applications

Registration techniques mentioned in Section 1.2 provides a variety of tools in medical imaging for better diagnosis and treatment of patients by enabling combined usage of different instruments in imaging. Multi-modality approach requires acquired images from different instruments to be registered to provide physician more information about patient in one image. Several medical image fusion examples will be given briefly in the following sections, before the introduction of X-Ray imaging fused with MRI.

1.3.1 PET-CT Fusion

PET is an imaging technique to obtain a three dimensional image or 2D projection of functional processes in the body by using of nuclear medicine. Imaging system forms the image by detecting pairs of gamma rays emitted indirectly by a radionuclide transferred to the patient with an active biological molecule. PET scans commonly used for detection of cancer and examining the effects of cancer therapy by characterization of biochemical changes in cancer. Spatial resolution of PET is limited by nature of positron annihilation (around 5mm). CT imaging, on the other hand, provides high spatial resolution (1mm pixel spacing), which leads to a combination of these modalities providing excellent complementary information for cancer assessment or when planing for tumor biopsy or surgery. Over the last decades several registration techniques are developed focusing on PET-CT image fusion (Sample fusion images are shown in Figure 1.4). Some instances were introduced by Alpert et. al. by using image's principal axes and center of gravity to form rigid 3D transformations, by Pietrzyk et. al. using a fully interactive method and by Maguire et. al. using user-identified anatomical landmarks and external markers [30][31][32].

This methods are developed when images are acquired at different times, nowadays in combined PET-CT machines registration process is seemless and fully automatic [33].

(a) (b) (c)

Figure 1.4 PET/CT scan of a 54-year-old female with a cervical cancer; the images show (a) the CT, (b) the FDG-PET and (c) the fused PET/CT image.(Taken from [4])

1.3.2 CT/MRI - Ultrasound Fusion

Medical image fusion between different cross-sectional modalities is widely used, like PET – CT fusion mentioned in section 1.3.1. Additionally, there are studies on including ultrasonography (US) in image fusion with cross-sectional modalities like CT and MRI to provide advantages like possible higher resolution for high frequency probes, the real-time images and the ease of imaging-guided biopsies or other interventional procedures. The real-time fusion of US images with pre-operative information from CT/MR scan is possible by using a magnetic tracking device and specially designed software, which register the scan plane of the US transducer[5] (Image registration sample shown in Figure 1.5).

Furthermore, by deriving an appropriate similarity measure based on artifacts and physical properties of ultrasound an assessment of the alignment of structures in ultrasound images and simulated slices generated from the CT data can be done. Validation of this method is done with various studies on patients with head and neck tumors and cervical lymph node metastases [34].

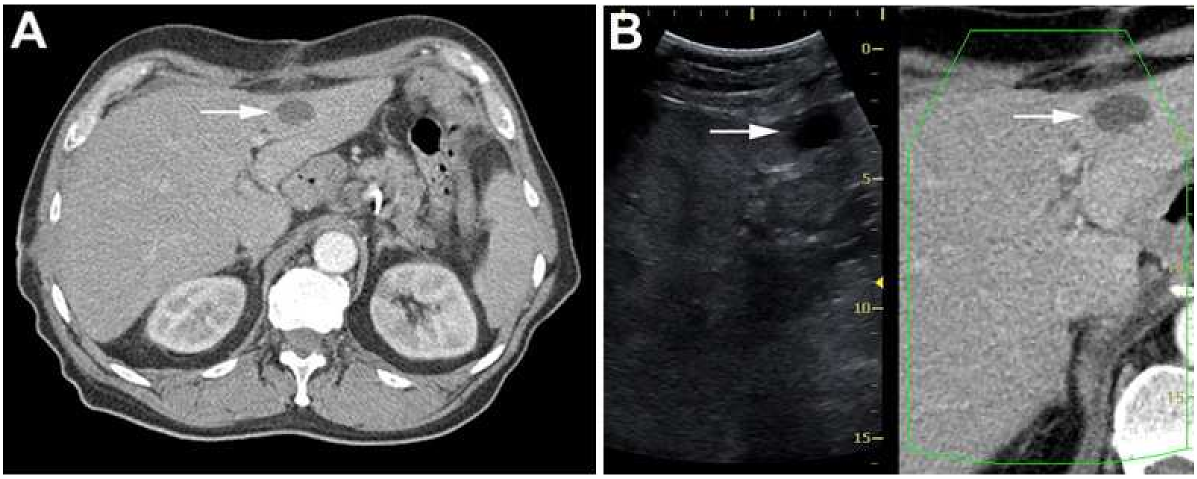

Figure 1.5 A patient with suspected metastases from cardia cancer and a cyst in the left lobe of the liver imaged with CT (A). Area is imaged with ultrasound too (B ,left). White horizontal arrow is indicating the cyst in A and B. Co-registered images are shown in B. sonogram image is to the left and reformatted CT image to the right. Area of the sonogram is indicated by the green box. (Taken from [5])

1.3.3 X-Ray-MRI Fusion

X-Ray fluoroscopy has definite advantages in temporal and spatial resolution as mentioned in Section 1.1.1. On the other hand, MRI provides excellent soft tissue contrast with full 3D anatomical details. A logical extension of complementary features of two modalities leads to a combined systems named X-Ray-MRI suites (XMR). There are several studies that has shown utilization of this dual-modality imaging environment: Dick et. al. tested feasibility and safety of invasive MRI during peripheral angioplasty. In their limited experience, invasive MRI appears to be feasible and safe with an active device throughout peripheral angioplasty. Patients can be safely handled in an XMR interventional suite since some of the critical parts of this procedure was done under XF, with backup of XF when things go wrong in MR guidance, which is still an experimental procedure [6] (Schematic diagram of XMR suite shown in Figure 1.6). Rhode et. al tested a combined system of two instruments (1.5T MR scanner and an XF mobile C-Arm system) connected with a sliding table. Registration process between image spaces is performed with help of infrared emitting diodes attached to the table and C-Arm. A tracking system avoids need of segmentation of the markers. However possible patient motion is ignored in this registration system since it uses only table position for registration **[35][36]**.

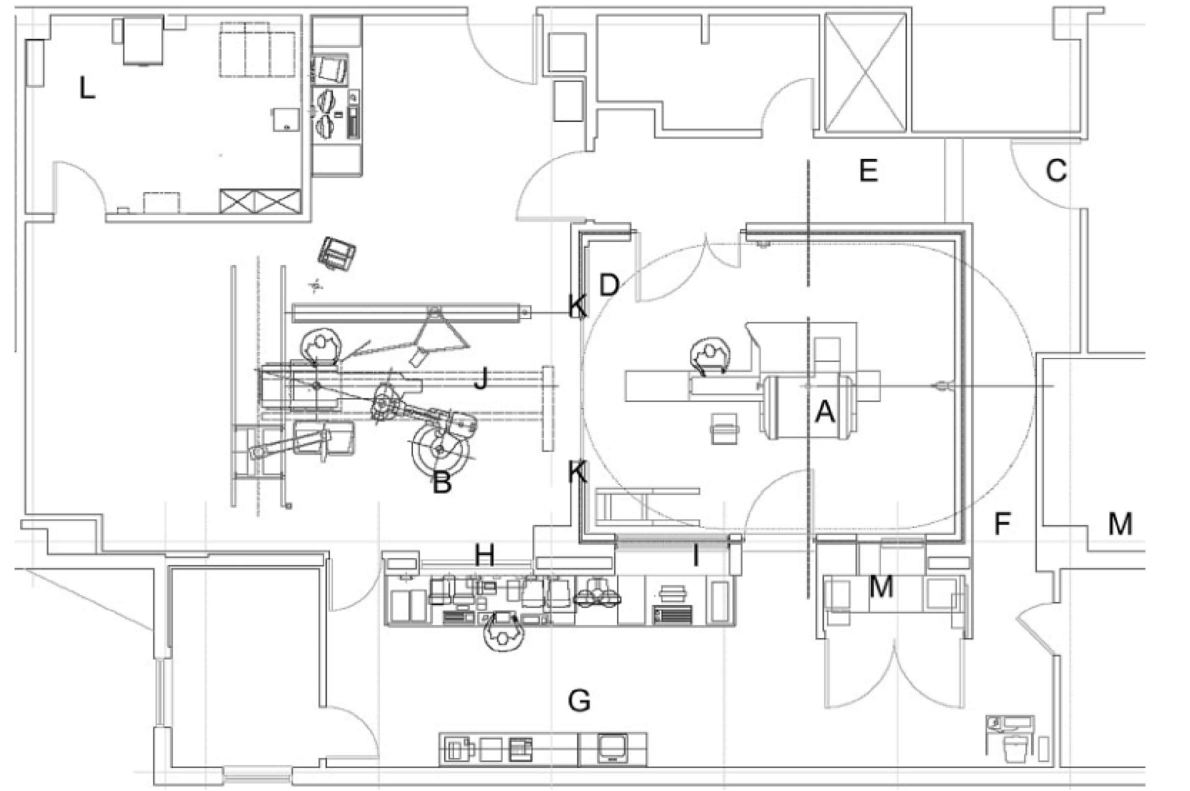

Figure 1.6 Schematic diagram of an XMR suite showing the relationship of the X-Ray and MR equipment. Components of the diagram are A: MRI system. B: X-Ray system. C: Entrance. D: 5 Gauss magnetic field line. E: Patient access, outside 5 Gauss line. F: Staff access, inside 5 Gauss line. G: Common control room. H: Shielded window into X-Ray laboratory. I: Shielded window into MRI laboratory. J: Rails for table pedestal. K: Shielded RF/X-Ray pocket doors. L: X-Ray instrument room. M: MRI instrument rooms. Diagram provided by Hannes Seissl (Taken from [6])

A solution for XMR suites with a registration method handling also the motion of patient during intervention with fiducial markers fixed on the patient is the focus of this study. Methods used for solution will be discussed in detail in the following section.

2. X-Ray Fused with MRI (XFM)

2.1 Concept

2.1.1 Introduction

The characteristic properties of XF and MRI make them good candidates to be used as a combination. XF has advantages like temporal and spatial resolution and easy visualization of catheters and additional devices during intervention; on the other hand it suffers from low soft tissue contrast and lack of cross sectional imaging which are crucial in guidance of the physician. In contrast, MRI has features; excellent soft tissue contrast and ability to image cross sections thorough the scanned volume. In contrast, MRI has several disadvantages; relatively low temporal resolution, limited patient access because of the shape of the magnet bore and instrument compatibility in high magnetic and RF fields.

As a logical extension of complementary features of both modalities mentioned above, combined X-Ray Fluoroscopy and MRI (XMR) suites are also proposed as an addition to the multi-modality imaging techniques previously mentioned in Section 1.3 assisting interventions. Combined usage of XF and MRI requires registration of images from both modalities which has several challenges.

First of all, there are distortions in images acquired from both modalities. XF images suffer from warping effect of image intensifier (II) and geometric distortions, which differs for each C-Arm position. This is discussed in more detail in calibration section 2.1.6, MRI images suffer from the non linear gradient warp distortions within the bore of the magnet. Both of these distortions have to be corrected before the registration between MRI and XF.

Another challenge is the dimensional and coordinate space differences between modalities. In XF, 2D projections of the interested volume are acquired, commonly from different vantages (primary, secondary angles). In MRI the images are acquired as cross-sections of the volume of interest and a 3D volume can be easily constructed. Because of the different coordinate spaces of two modalities, registration of 2D images of XF on 3D volume of MRI requires knowledge of projection geometry. Registration between XF and MRI images can be done using several approaches mentioned above in registration techniques. In our study the approach of point based registration is employed with the feature points formed by centroids of dual modality markers, discussed in detail in Section 2.1.4.

Additionally, registration process should handle real-time actions on XF instrument with time performance requirements and should not add too much overhead on the existing XF system. Proposed XFM procedure and used methods and materials will be discussed in next sections. With the detailed discussion of the procedure, requirements of the proposed fusion software tool will be linked to the corresponding steps with the codes attached in the format REQ_XFM_(#ID) (requirements discussed in detail in Section 3.2.1).

2.1.2 Workflow

A typical XFM procedure as proposed and employed in previous studies [9] consists of the steps below:

1. The subject is taken to an MRI scan with a multimodality marker belt (shown in Figure 2.1).
2. An marker contrast based MRI scan with 3D gradient echo imaging is performed with image parameters: TE/TR = 1.18/2.37 ms, flip angle = 17º, field of view (FOV) = 400x300x230 mm, acquisition matrix = 256x192x61 is done.
3. Additional anatomical and functional MR scans focusing on volume of interest are performed.

4. The patient is taken to XF unit.
5. A set of images are acquired from different PA and SA angles.
6. Acquired images from XF and MRI scans are transferred to the PC with fusion system (shown in Figure 2.2).
7. Segmentation of the markers in XF and MR images is performed. (In XF 2D segmentation, in MRI 3D segmentation)
8. Distortion correction is performed on acquired 2D coordinates of the segmented markers.
9. Marker coordinates are calculated in 3D from MRI and XF images.
10. Registration of two clouds of points in 3D is performed.
11. A transform matrix from MRI space to XF Space is calculated with the information of registered points.
12. Important points and surfaces are determined by the physician on MR anatomical images. These contours are saved in MRI space.
13. During the intervention, XF Instrument parameters are tracked and the surfaces and/or points defined by physician are transformed from MRI space into XF space using transform matrix and fused on "real time" on top of XF images to guide the physician.

Additional background information will be given in the following section for some of the key steps and components listed above.

Figure 2.1 Multi-modality marker belt used in XFM study. Markers are located on the belt with specific pattern for the ease of segmentation of XF images. (Taken from [7])

2.1.3 Materials and Methods

2.1.4 Fiducial Markers

Our XFM system employs image registration routines which are based on the matching of fiducial markers. The markers used in this study are ellipsoid shaped plastic capsules filled with a home–made solution. This solution consists of two contrast elements: 5mM Gd-DTPA (Magnevist, Berlex, Montville, NJ) and iodinated contrast solution (Visipaque, Amersham Health, Buckinghamshire, UK). Gd-DTPA solution provides brighter areas in MRI scans while iodinated solution provides darker areas in XF images. Fixed positioning of external markers on patient is provided by a belt worn by the patient (shown in Figure 2.1).

2.1.5 Imaging

Images used in XFM study were acquired from a Siemens Sonata 1.5 T scanner and an Axiom Artis cardiac single plane XF system. Patients can be transferred between two imaging systems on a cradle that slides along a motorized table with no change in patient position on the table (Figure 2.3). Positions of the fiducial markers are determined in the MR scanner using 3D gradient echo imaging sequence. Full volume of interest with all markers was acquired in 28 seconds with the imaging parameters: TE/TR = 1.18/2.37 ms; flip angle = 17^{o}; field of view (FOV) = $400\times300\times230$ mm; acquisition matrix = $256\times192\times61$ voxels; bandwidth = 1300 Hz/pixel. An XF system

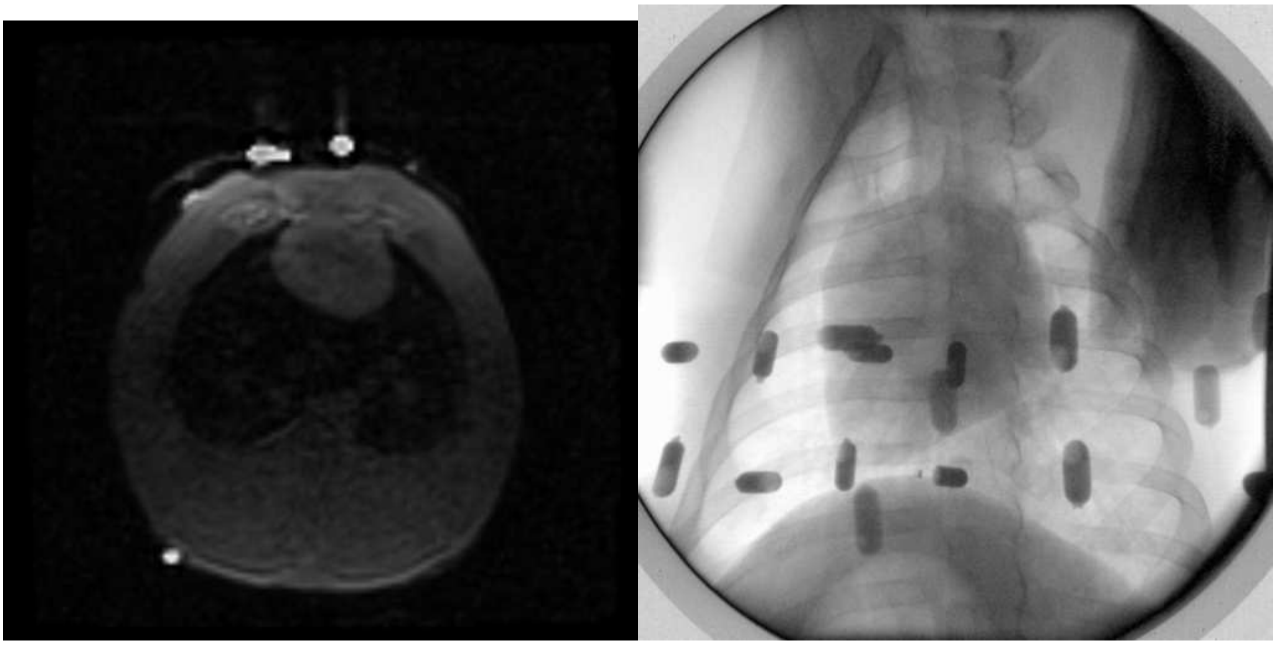

Figure 2.2 Sample images showing marker's contrast effect on MRI (left) and XF (right) modalities.

with a conventional image intensifier (II) with a maximum nominal diameter FOV of 330 mm is used. Images acquired in 512×512 pixels format. XF imaging parameters like primary angle (PA), secondary angle (SA), source-to-intensifier distance (SID), and FOV were changing during experiments and corresponding values will be mentioned in following sections.

2.1.6 Distortion Correction

2.1.6.1 Distortion Correction in MR Images. The magnetic gradients used in MR imaging process are routinely assumed to be linear within the bore of the magnet. Nevertheless; the gradients are non-linear at the edges of the imaging volume in practice and also not constant in the z direction (along the magnetic field) which results in image distortion. All distortions in the images mentioned (images of 3D Marker scan and 3D VOI scan) are first corrected with image correction software supplied by Siemens before transferring images to XFM Fusion Workstation [37].

Figure 2.3 A combined X-Ray and MRI interventional suite. Two systems can be used independently or together. Patients can be transferred between labs on a cradle that slides along a motorized table. Each room can display real-time images, instantaneous hemodynamics, and imaging control to the operator. Both share a common control room for support staff.(Taken from [8])

2.1.6.2 Distortion Correction in X-Ray Images. XF images suffer from pincushion and S-shaped geometric distortions. Pincushion type distortion is due to the warping effect of image intensifier (II). X-Rays reaching the proximal face of the II are converted first to photons and then to electrons by an input screen. Resulting electrons travel the length of II, where the projected image is formed onto the output phosphor. Because of the electron physics requirements input screen has a curved shape like a sector of a sphere (Figure 2.4). Due to the projection of an object plane onto the curved input screen a pin-cushion type distortion is formed on the resulting image. This type of distortion is independent of the orientation of C-Arm.

Another type of distortion results from the local magnetic field effecting electron beams inside the II. Magnetic field effect has two components: Longitudinal component of the effecting magnetic field (directed along the axis from source to II) forms a transverse force on the electrons resulting in a bulk rotation on the image. Transverse component of the field forms a force that has both longitudinal and transverse components resulting in a translation of entire image. Resulting effect of combination of these components is an S-shaped distortion on the image. This type of distortion depends on the orientation of the C-arm because of the re-orientation of the II's longitudinal and transverse directions and heterogeneous property of local magnetic field. This has two components in a XMR setting, first one earth's magnetic field (similar to all other XF systems), the second one is the fringe magnetic field from the MR system nearby. This is unique for XMR systems and cause higher distortion problems and additional unique challenges for XFM. This requires distortion correction strategy to be dependant on the orientation of the C-arm.

A distortion correction procedure is proposed by Gutierrez et al. [9] as follows:

- A sheet of plastic with metal rings placed at 1 cm intervals is attached to the front face of II.
- Images are acquired from different PA and SA values typically ranging between -50 $^\circ$ and 50 $^\circ$ for both PA and SA. Could be extended to other angles used (like

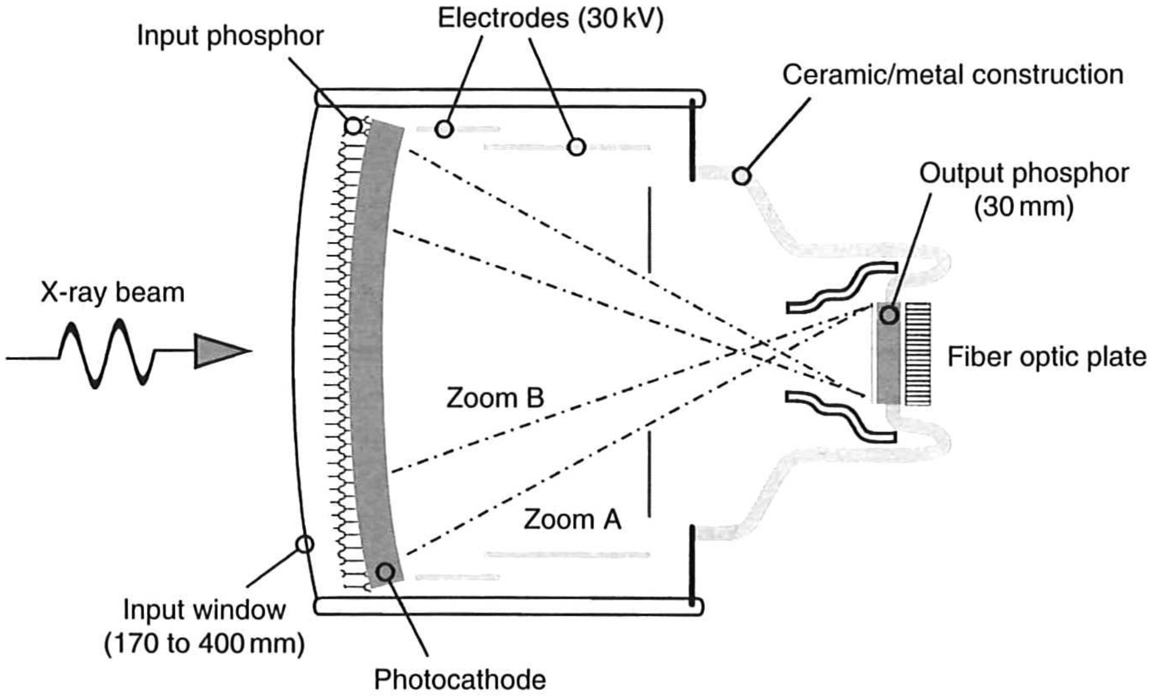

Figure 2.4 Image Intensifier Design. The four main components of an image intensifier: 1.The vacuum tube 2.Input layer that converts the X-Rays into electrons 3.Electronic lenses that focus the electrons 4.Output phosphor that converts the accelerated electrons into visible light

lateral) for specific procedures.

- Observed locations of the metal rings are segmented automatically in each image forming a 2D coordinate array of observed rings. (Shown in Figure 2.6)
- 2D coordinates of the segmented metal rings formed a matrix.
- 5th order fitting polynomials are calculated with input data points for x and y coordinates (Polynomial interpolation discussed in detail by Gutierrez et. al. in his thesis [9]).
- Calculated coefficients are used to interpolate the whole pixels with 2D coordinate (x_i, y_i) of the distorted image to the corrected image with 2D coordinates (x_c, y_c).

2.1.6.3 Geometry Calibration of C-Arm . XF images are 2D projections of a 3D volume. 3D distortion as discussed in previous section should be corrected before taking projection images from the scene, when we replicate the physics or perform back-projection in XF. 3D to 2D transformation of XF images depends mainly on the parameters below:

- Primary angle (PA)
- Secondary angle (SA)
- Source to Image Distance (SID)
- Intensifier Size (IS)

PA and SA values determine the relative position and orientation of the 2D projection plane (physical location of II screen) in 3D. SID and IS values determines the magnification ratio of the 2D projection. 3D to 2D projection can be obtained by the following equation:

$$\begin{bmatrix} x_h \\ y_h \\ z_h \end{bmatrix} = \begin{bmatrix} -S_i \frac{SID}{IS} & 0 & -S_i \\ 0 & -S_j \frac{SID}{IS} & -S_j \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} \tag{2.1}$$

And

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} x_h/z_h \\ x_h/z_h \end{bmatrix} \tag{2.2}$$

Where (x_k, y_k, z_k) refers to XF world 3D coordinates and(x_h, y_h, z_h) refers to XF 2D homogeneous coordinates. S_i,S_j are the number of pixels in x and y directions. And (u, v) is the final 2D image coordinates computed from their counterparts in homogeneous coordinate system. This approach separates the non linear projection process

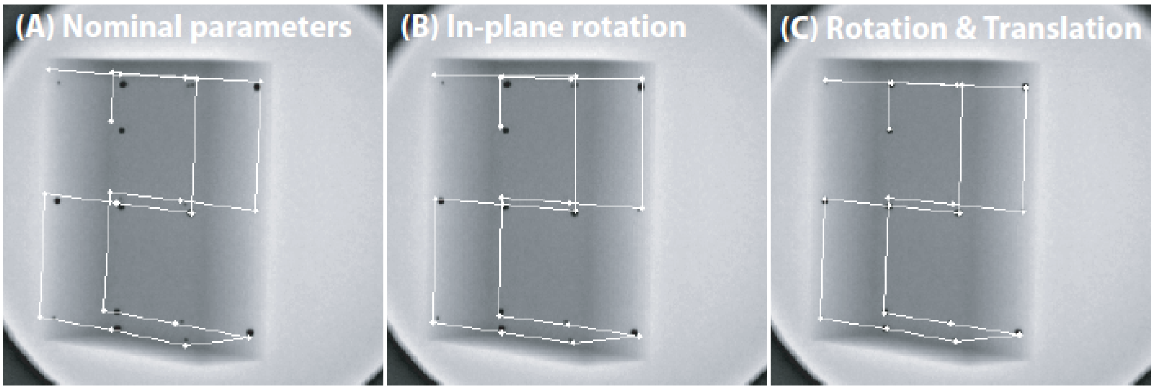

Figure 2.5 3D projection of metals beads reconstruction (A) with no calibration performed. (B) with in-plane rotation is performed . (C) with in-plane rotation and translation performed. (Taken from [9]).

into a linear matrix calculation (eq. 2.1) and a simple nonlinear division components (eq. 2.2).

There exists an additional residual in-plane rotation and translation due to effect of gravitation on C-Arm and intrinsic distortion in reference grid that can not be detected in its ideal position. In his study Gutierrez et. al. [37] proposed an extra step in projection process to handle the residual distortion (registration results before and after in-plane translation and rotation are shown in Figure 2.5):

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = R_i . \begin{bmatrix} u \\ v \end{bmatrix} + T_i \tag{2.3}$$

In the formula above R_i stands for the in-plane rotation matrix and T_i stands for the 2D translation matrix. Calibration of these values is performed with the following procedure [37]:

1. A phantom with 19 metal beads in known relative positions is designed for calibration process (Shown in Figure 2.6).
2. A set of images with changing PA values from -45 to +45 with 15 increments are

acquired in XF.

3. Metal beads are segmented in XF images and 2D coordinates of beads are used to reconstruct 3D coordinates of the beads in XF space. RMS 3D Euclidean distance between known positions and reconstructed positions is calculated (3D error).

4. With 3D to 2D transform mentioned above, reconstructed bead locations in 3D are projected back to 2D images and RMS distances between actual beads segmented and projected ones are calculated (2D error).

5. An optimization is performed to minimize sum of 3D and 2D errors.

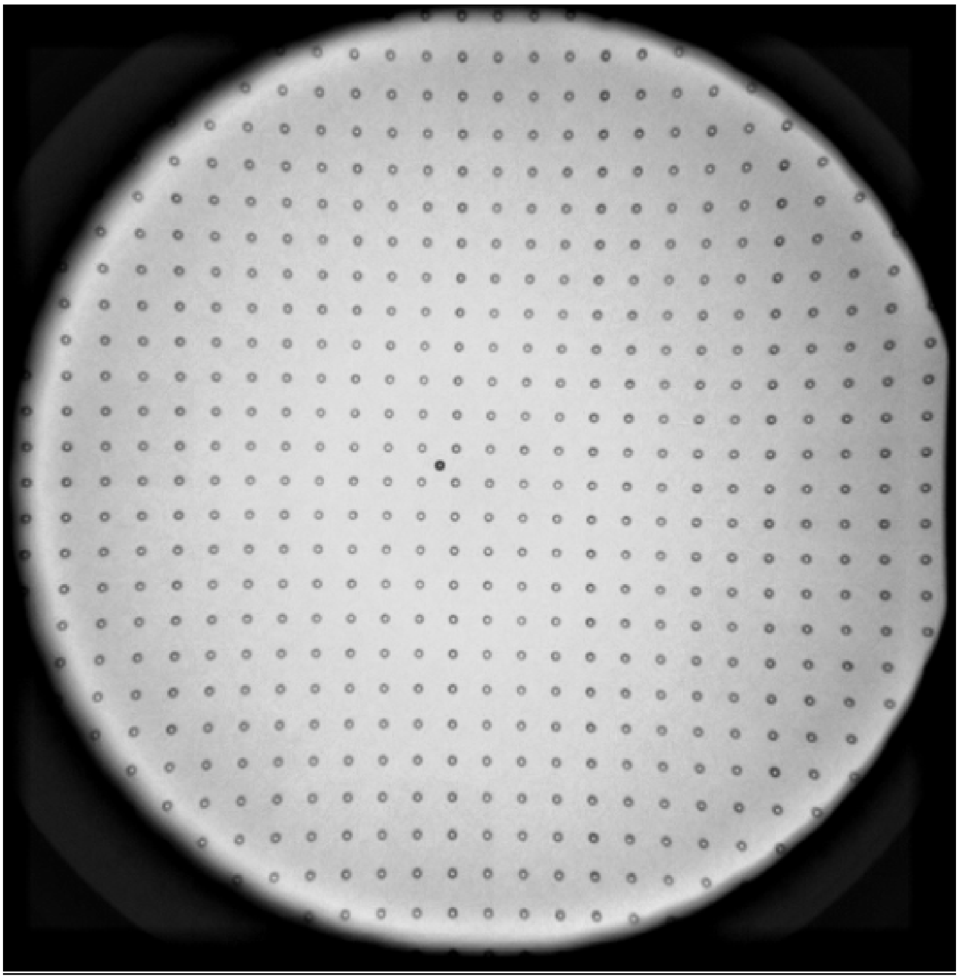

Figure 2.6 Image of grid phantom used in distortion calibration procedure without distortion correction. Distortion is more visible at the edges.

2.2 Previous Studies and Softwares in XFM

In previous studies in our group on XFM a Matlab based software is implemented for guiding the intervention in real-time with an integrated XFM procedure. XFM procedure integrated with software aid is discussed in detail by Gutierrez et. al. in his thesis [9] (XFM procedure flow proposed is shown in Figure 2.9). Additional to proposed XFM procedure distortions on XF images is discussed in detail by Gutierrez et. al. and a practical global distortion correction method is proposed in his study [37]. Registration method utilized by software solution proposed by Gutierrez et. al. is semi-interactive with user identifying marker positions in 2D images. Sönmez et. al. proposed an improvement over existing software with a full-automatic point matching and registration tool in his thesis [7]. His automatic registration tool employs point-based rigid registration method with homologous point sets. Homologous point sets are provided by a novel matching algorithm proposed by Sönmez et. al. based on similarity of triangles formed by point sets according to similar side lengths (Sample registration results shown in Figure 2.7).

All previous works on XFM software mentioned above are based on extrinsic non-invasive rigid registration method with external fiducial marker based approach. Durmaz et. al. discussed an intrinsic rigid registration method with an intensity based registration approach in his thesis [10] (Sample registration results shown in Figure 2.8).

This study is based on the previous efforts on XFM software solution mentioned above. Main goal in this study is to investigate systematically the existing software solution with a subsequent complete re-implementation to optimize performance as requested by all of our clinical partners. In addition to performance improvements, with implementation in XIP platform it is intended to achieve hardware integration support provided by means of standards proposed by DICOM WG23 group. With information provided by previous studies, our aim is to supply enhancements on various post-processes utilized in XFM software and with a new UI design enabling smooth integration of software aid with clinical process.

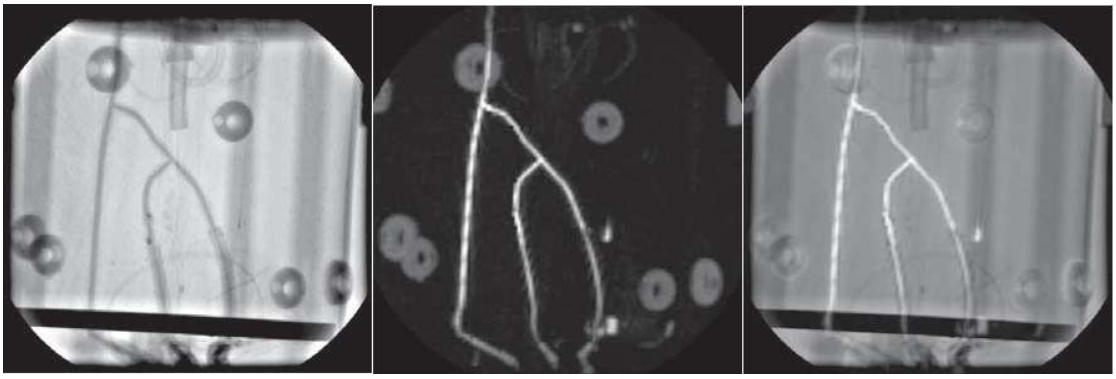

Figure 2.7 Point-based registration results with Matlab based XFM software (From [9]).

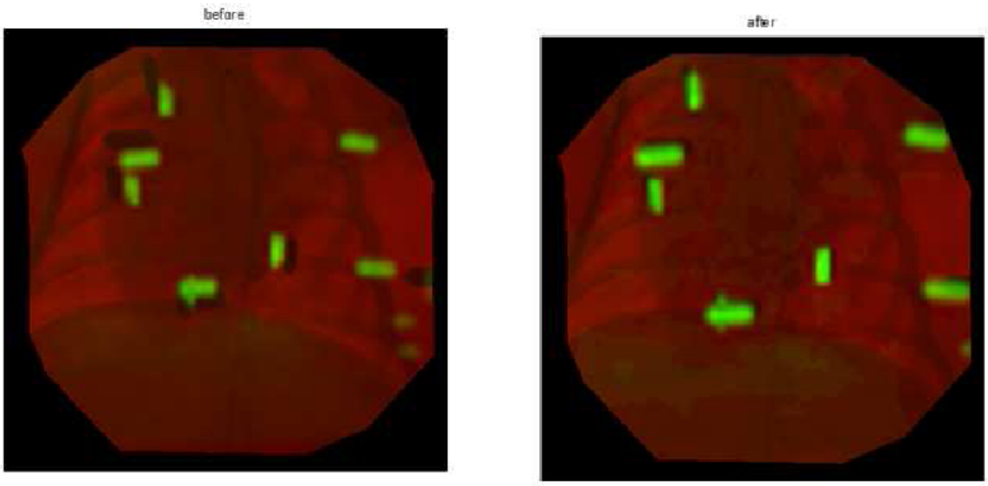

Figure 2.8 Intensity-based registration results by study of Durmaz et. al. (From [10])

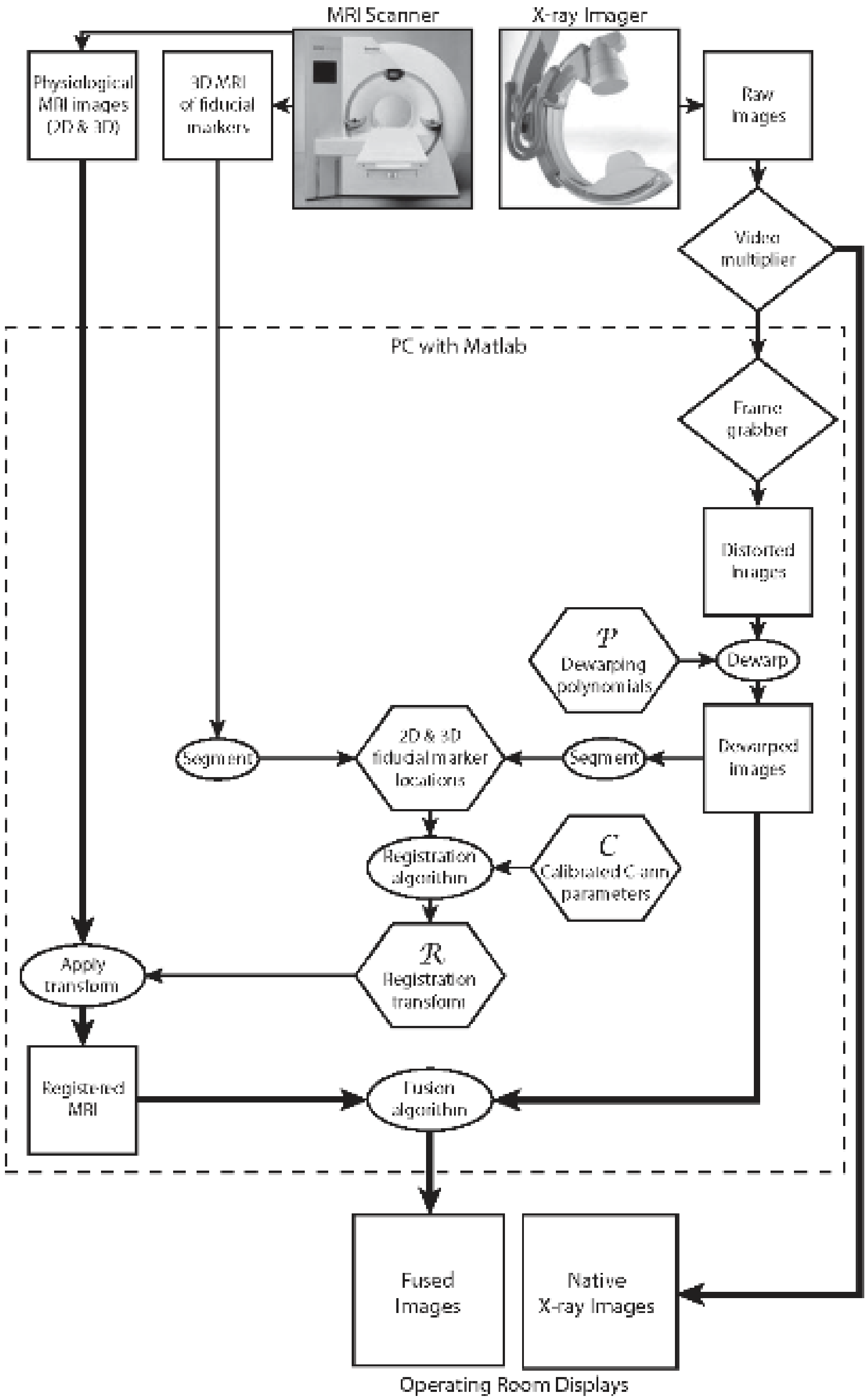

Figure 2.9 XFM procedure flow chart proposed by Gutierrez et. al. (From [9])

2.3 Platform Requirements

1. Program portability: Software should be executed as a standalone application independent of a third-party program. It should be deployed in a new PC without need of a another software.

2. Real-time XF image capture performance: Software performance should meet a minimum limit of screen refresh rate in capturing XF screen (minimum 15 frames per second) without occupying too much extra memory (A buffer size for storing 5-10 frames,occupy 2MB each, maximum memory usage should be 50 MB).

3. Extensibility: Software should encapsulate several functional modules for image processing which could potentially be extended by additional functionality in future studies.

4. Code economy: Software should be implemented in a manner that multiple use of same functional code should be avoided not to enlarge the code and not to complicate potential implementation changes for future developers who would want to understand and alter the existing system.

5. Ease of design: Software design should be intuitive and the existing functionalities should be easily comprehended by other developers. A graphical tool for software implementation design would be a great assistance for the ease of design.

6. Real-time response: Software will be running in an interventional suite which is definitely a time critical environment. Therefore it should handle rapid flow of data coming from real-time parameters gathered from several medical instruments and should be able to process these data and provide user with output also in real-time. Latency of system output is one of the most important criteria.

7. Ease of work-flow: As mentioned above, medical environment, that the software will be used, requires smooth work flows for all users. Software should avoid extra confirmations and detours along the study which would prevent user from rapid actions.

2.4 Platforms Tested for Software Development

As proposed in the previous sections, X-Ray Fused MRI software has strict real-time performance needs. To fulfill these needs and avoid cumbersome work flow structures, our system design effort focused on C++ as the application development language because of time performance advantages. During our search for appropriate image processing libraries we considered Open Inventor based solutions, ITK (Insight Segmentation and Registration Toolkit) and VTK (Visualization Toolkit) libraries, and 3D Slicer as possible candidates. Detailed information about these candidates are given in the following sections.

2.4.1 Open Inventor

Open Inventor is an object-oriented 3D toolkit which provides a programming model based on a 3D scene database therefore simplifies graphics programming effectively. In addition it is offering a comprehensive solution to interactive graphics programming problems. A rich set of objects is included such as cubes, polygons, text, materials, cameras, lights, trackballs, handle boxes, 3D viewers, and editors which speed up programming time and extend 3D programming capabilities [38]. Basic properties of Open Inventor are:

- It is built on top of OpenGL
- It includes standard file format defined for 3D data interchange
- It presents a simple event model for 3D interaction
- It introduces animation objects called Engines
- It enables high performance object picking
- It is platform independent
- It is portable 3D graphics development system across platforms

- It provides Postscript printing
- It supplies programmers with extensible objects

OpenGL (OGL) is a low level library which is simply used to render lists of simple polygons rapidly. But obtaining more complex and practical functions like "draw a house", the object must be separated by the programmer into a series of simple OGL instructions which will be sent into the engine for rendering. OGL performance is depends significantly on the way the instructions sent into the system which requires user to know which instructions to use and the order of instructions. A significant amount of programming has to be done even for simple programs.

Open Inventor (OI) addressed this drawback of OGL usage, and aims to provide a common base layer for easy start in 3D programming with OGL. Objects that can be used by programmers could be sub classed from a number of pre-defined shapes like cubes and polygons, and then can be extended easily into new shapes. The object to be drawn was placed in a scene graph run by OI, with the system applies rendering on objects in the graph automatically. A number of controller objects and systems for applying them to the scene are also provided by OI to make common interaction tasks easier. In addition OI presents a common file format for storing 3D objects, and the code to automatically save or load an object from these files [39].

2.4.2 ITK (Insight Toolkit)

ITK is an open-source, cross-platform system aims to provide developers with an extensive suite of software tools for image analysis and processing. Developed through extreme programming methodologies, ITK provides developers leading-edge algorithms for registering and segmenting multidimensional data [40]. ITK is developed with the objectives below:

- Support for the "Visible Human" Project [41]

- Establishment of a foundation for future image processing research
- Creation of a repository of fundamental image processing algorithms
- A platform for advanced product development
- Support commercial application of the technology
- Creations of conventions for future work

The Insight Toolkit (ITK) is mainly an open-source software toolkit for image registration and segmentation. Segmentation is a process of identifying and classifying data in images more specifically in a digitally sampled representation of the captured scene. A typical sampled representation is an image acquired from such medical instrumentation like CT or MRI scanners. Registration is the process of alignment or developing correspondences between data. For instance, in the medical environment, a CT image set can be aligned with a MRI set in order to combine the information contained in both. ITK is implementation in C++, it is portable across platforms, with the use of CMake build environment to manage the compilation process. Additionally, an automated wrapping process provides interfaces between C++ and interpreted programming languages such as Tcl, Java, and Python. In this manner developers are able to create software using a variety of programming languages [42].

2.4.3 VTK (Visualization Toolkit)

The Visualization ToolKit (VTK) is basically an object oriented software system focused on 3D computer graphics, image processing, and visualization. VTK is consisting of of a C++ class library and several interpreted interface layers including Tcl/Tk, Java, and Python [43].

The VTK model is based on the data-flow paradigm extensively used by commercial systems. In this paradigm, modules are linked together into a network. As the data flows through the network, module perform the algorithmic operations on it.

Visualization network execution is controlled in response to demands for data (demand-driven) or in response to user input (event-driven). Advantages of this model are being flexible, and being able to quickly adapt to different data types or new algorithmic implementations.

A wide variety of visualization algorithms are supported by VTK including: scalar, vector, tensor, texture, and volumetric methods; and also advanced modeling techniques such as: implicit modeling, polygon reduction, mesh smoothing, cutting, contouring, and Delaunay triangulation. Additionally, several imaging algorithms have been integrated into the system. VTK is a cross-platform toolkit runs on Linux, Windows, Mac and Unix platforms. Also ancillary support for 3D interaction widgets, two and three-dimensional annotation, and parallel computing are included in the system.

Visualization model in VTK consists of two basic types of objects: process objects and data objects. The modules or algorithmic portions of the visualization network are called Process objects. Data objects represent and enable operations on the data that flows through the network. There are three types of Process objects:

- Sources
- Filters
- Mappers

The network is initiated by source objects and they generate one or more output data sets. Filters require one or more inputs and generate one or more outputs. Network is terminated by mappers, which require one or more inputs [44].

2.4.4 3D Slicer

3D Slicer is a platform providing image registration, image segmentation, vascular modeling, data import/export, processing of diffusion tractography and graphical

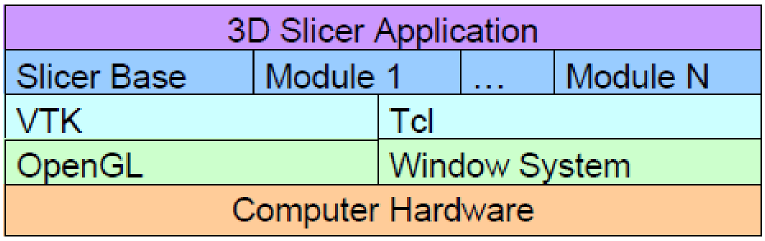

Figure 2.10 Architecture of 3D Slicer Platform

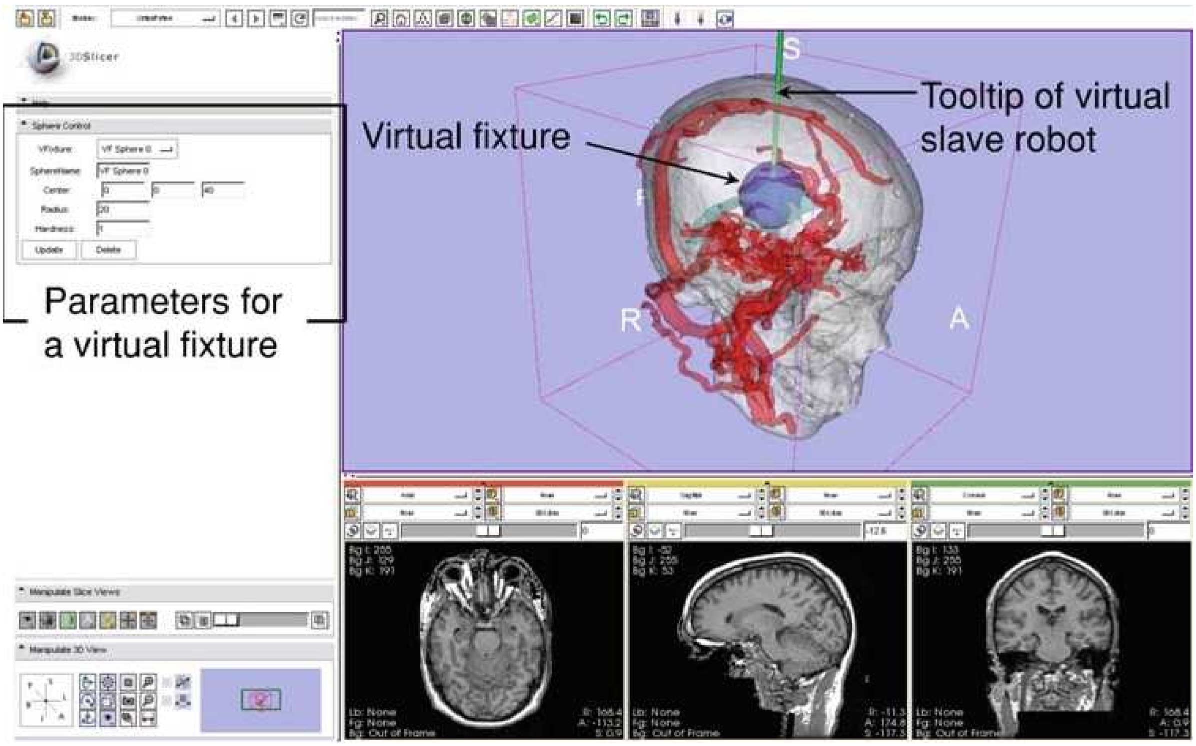

Figure 2.11 A screenshot of 3D Slicer User Interface (From [11])

processing unit (GPU) enabled volume rendering. Aim of 3D Slicer project is to provide the platform with mentioned functionalities for a variety of applications through a community-development model. Slicer is based on a large extend on VTK and a common library of Tool Command Language (Tcl) script code for the implementation of user interface written in Tcl/Tk windowing toolkit. General architecture of 3D slicer platform is shown in Figure 2.10 [45].

A variety of visualization capabilities are provided by 3D slicer like:

- Display arbitrarily oriented image slices
- Build surface models from image labels
- High performance volume rendering

Additionally, a rich set of annotation features (fiducials and measurement widgets, customized color maps) is supported by 3D Slicer. It can be extended for development of both interactive and batch processing tools to be used in various medical applications.

2.4.5 Evaluation of Tested Platforms

ITK with VTK platforms satisfies the functional requirements like image segmentation, registration and fusion of XFM Suite. However, ITK and VTK platforms should be used together because of their complementary features. Our research of combined usage of ITK and VTK platforms revealed that there are problems in integration of two platforms which is not suitable for XFM Suite. Other candidate platform, 3D Slicer, has powerful segmentation, registration and volume rendering capabilities. On the other hand, it suffers lack of a standalone application output which is mandatory for XFM Suite. Therefore our overall evaluation leads us not to use any of the platforms mentioned above for XFM Suite development. Throughout our research about potential platforms we reached information about Extensible Imaging Platform (XIP) which will be discussed in detail in Section 2.5.

2.5 Selected Platform - Extensible Imaging Platform (XIP)

XIP platform is an Open Source framework a C++ platform for Medical Imaging and Visualization application development. It is mainly based on an open source image processing library called Open Inventor. It offers development of “plug-and-play" applications across multiple computing environments. Besides XIP provides several image processing and visualization modules that can be extended and used by researchers to develop medical applications and solve clinical problems. XIP is created by NCI (National Cancer Institute) funding and it is a part of caBIG initiative [46]. It is also maintained and contributed by Siemens Corporate Research [47].

XIP is created with the goal of defining an implementation platform which information and algorithms provided by several research centers all around the world can be shared, optimized and most efficiently integrated into ongoing efforts [12]. XIP platform has focus on the priorities listed below:

- Increasing usage of imaging-based end points in clinical trials
- Increasing uniformity of the image analysis
- Ability to have cost efficient and easier access to specific post-processing applications at multiple sites
- By usage of already approved libraries streamlining the Federal Drug Administration (FDA) approval process
- Making it possible for researchers to develop and evaluate new approaches to radiological imaging problems easily, and using them in a translational research setting

Besides these priorities XIP is created as a reference implantation of DICOM WG23 standard plug-in interface specification. This property will enable an application developed according to the standard API, to work with any hosting system supports WG-23 Interface as shown in Figure 2.12.The common infrastructure needed by all applications listed below will be provided by hosting system:

- Login
- Audit Trail
- Security

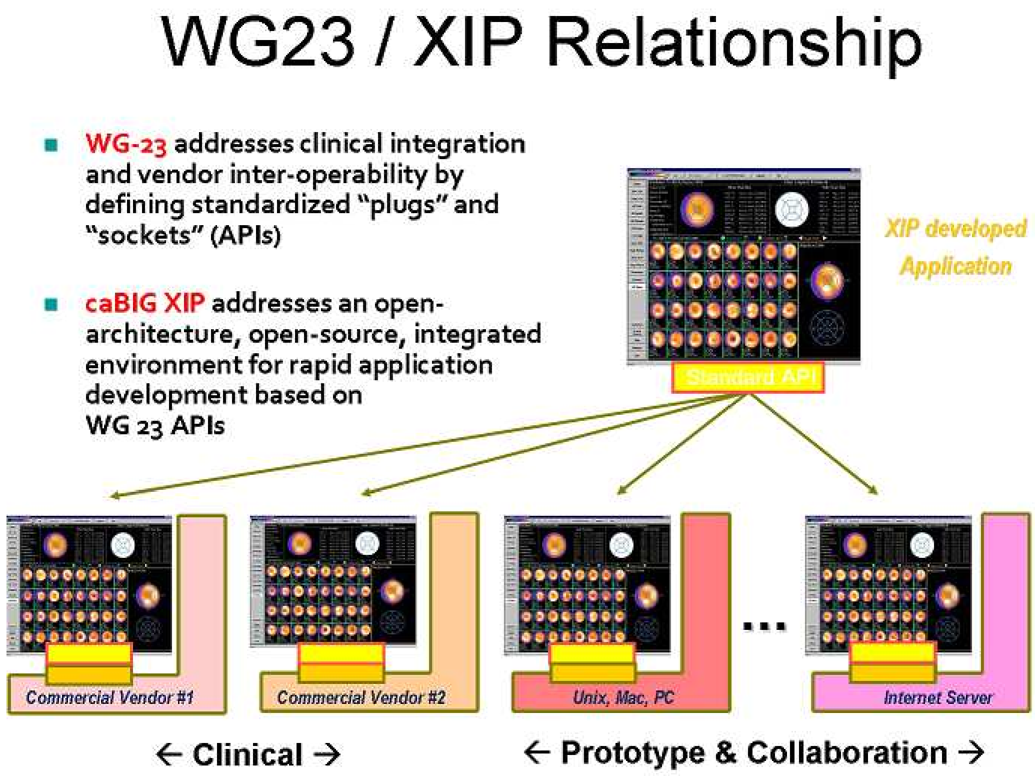

Figure 2.12 WG 23 / XIP Relation Portability of XIP Applications (From [12])

- Work list
- Database
- Network Access
- Task/Resource Management

Hosted application will be able to work with abstract data models instead of depending on the underlying storage format. There will be two main interfaces in the plug-in system: "Application" interface will hold the methods that hosting system uses to control and feed data to the hosted application while the "Host" interface includes the methods that will be used by hosted application to provide outputs to the hosting system and notify it about the status of the application.

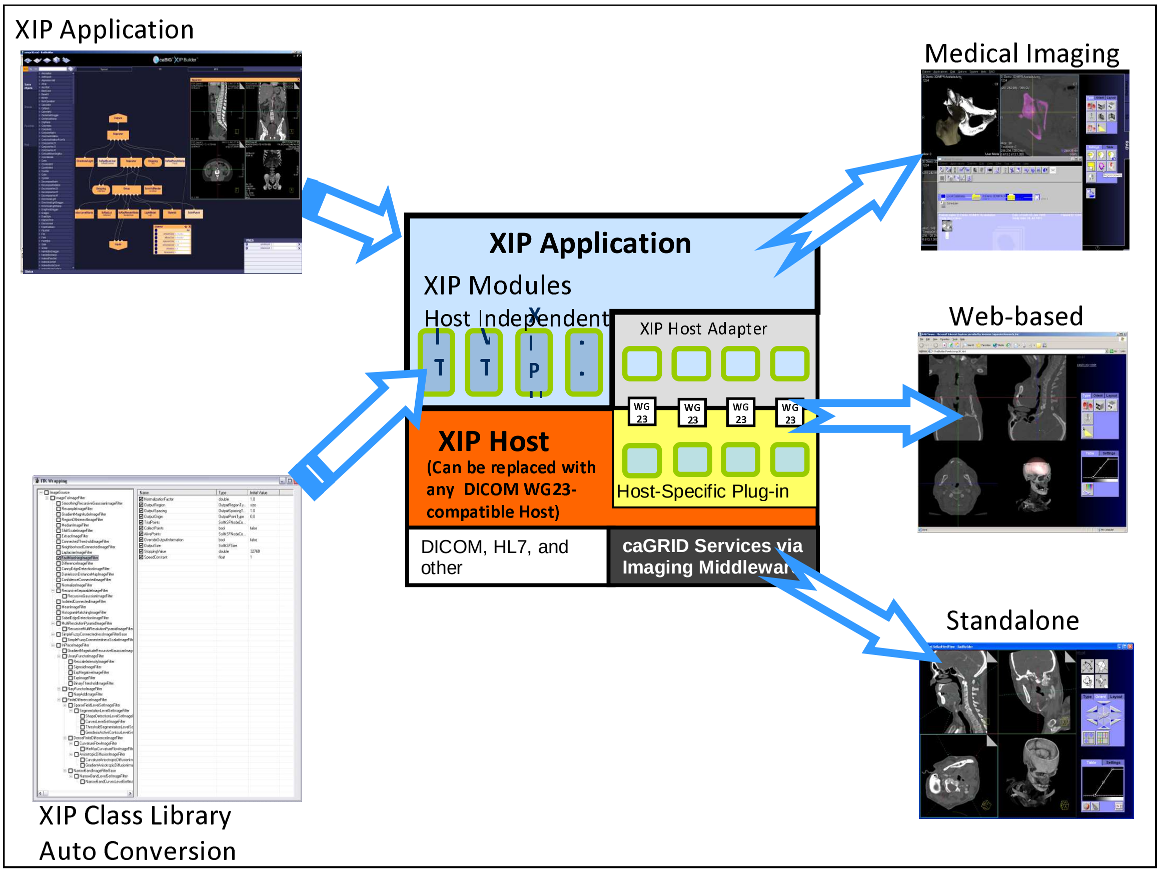

Figure 2.13 XIP medical application development flow (From [12])

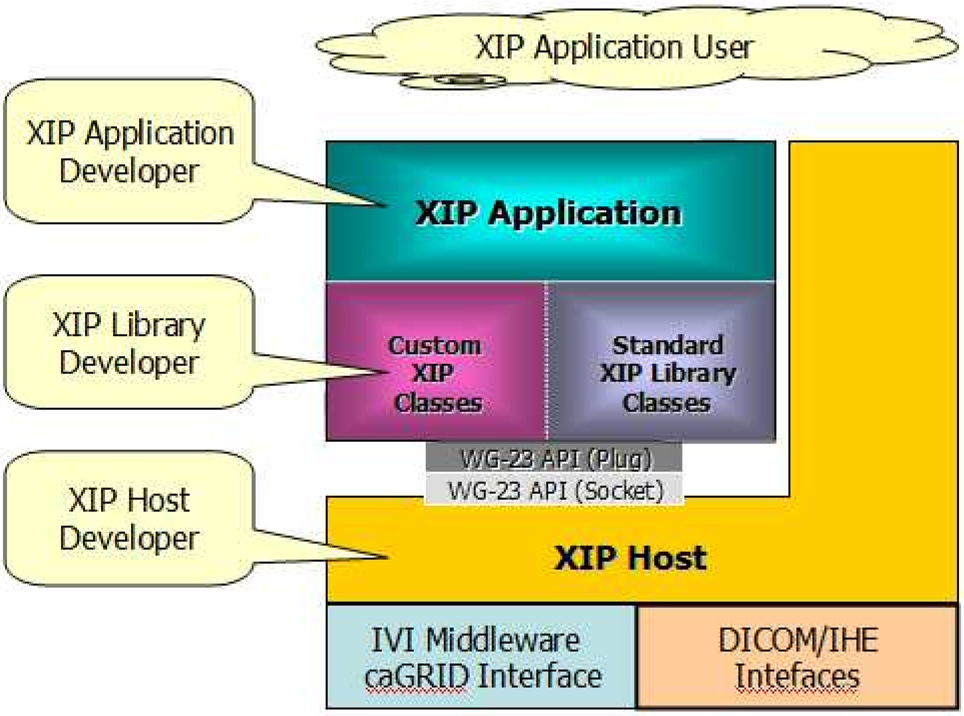

Figure 2.14 XIP application DICOM WG-23 compatible "Plug& Play" architecture (From [12])

XIP has several modules dealing with different functionalities in medical imaging these modules and brief descriptions are stated below:

- XIP Builder: Visual Programming Interface to design XIP scene graphs which are application work flow charts.
- XIPIvCore: Modules wrapped from Open Inventor library constructing the main modules for program structure in XIP.
- XIPIvCoreGL: Modules for OpenGL support that are not provided by Open Inventor module.
- XIPIvOverlay: Modules that provide overlay objects (markup) support for image annotations and measurements over images.
- XIPIvRenderer: Modules that provide 3D images operations and rendering in 3D.
- XIPIvDicom: Modules that provide DICOM support based on DCMTK library.

- XIPIvITK: Modules wrapped from ITK library provide functional objects about image segmentation and registration.
- XIPIvVTK: Modules wrapped from VTK library provide functional objects about visualization and rendering.

As a general evaluation of XIP platform we can discuss the correspondence between the platform requirements mentioned in section 2.3. List of the requirements is given below with correspondent feature of XIP:

1. Program portability: XIP implementation can be compiled as a standalone application which provides portability without a third-party program.
2. Real-time XF image capture performance: XIP image capture module implemented as a prototype is tested for capture performance and fulfills the requirement.
3. Extensibility: XIP platform provides generic interfaces with using Open Inventor architecture enabling developers extending the existing modules easily.
4. Code economy: Usage of existing modules imported from ITK, VTK and Open Inventor avoids developer to re-implement segmentation and post-processing functionalities. Furthermore an implemented module can be reused in a scene-graph with multiple instances.
5. Ease of design: Usage of scene-graphs in implementation of the applications provides other developers easily comprehend the existing architecture and modular structure and modify it if needed.
6. Real-time response: XIP platform provides real-time changes on the data rendered in the output. Therefore XIP enables a real-time adaptation of the output with according to input flow.
7. Ease of work-flow: XIP platform provides support for implementation user interfaces (UI's) using QT or HTML enabling developers to implement simple UI's for medical staff.

As shown in the correspondence list above XIP platform provides us the required flexibility and functional modules for XFM Suite development.

3. XFM Suite with XIP

3.1 Introduction

The focus of this study is to implement a software which is capable of guiding a physician throughout the intervention. There are various XMR solutions proposed previously [9][2][48]. Main aim is to register a priori MRI images over live X-Ray images. As previously mentioned, the registration method in this study employs a point based registration technique. Therefore mutual points from fiducial/external markers have to be identified and registered first. This includes both selection of right points to be identified in both modalities and matching them correctly. Former step is handled by image processing routines utilized on XF and MRI images. If it is perfect the matching step is easy. But due to overlapping markers, failure to include all necessary volume of interest not all markers are identified, some extra non-existing additional markers could be found. So matching process is critical. We expanded the work of Sönmez et. al. [7].

As commercial medical softwares are subject to strict regulations, our solution should also meet the necessary performance and ease of use requirements. Some of the requirements mentioned in section 2.3 will be re-mentioned in the following sections from the clinical perspective below as they have an important role in the design of the software.

3.2 Software Requirements

3.2.1 XFM Software Functional Requirements

3.2.1.1 MRI Image Acquisition <REQ_XFM_1>. Loading of the acquired MRI images to XFM Suite via DICOM file transfer. User should be able to see MRI images and navigate through the series of slices and images.

3.2.1.2 X-Ray image acquisition (Offline) <REQ_XFM_2>. Loading of the acquired XF marker detection images to XFM Suite via DICOM file transfer. User should be able to see images and navigate through the series of slices and images.

3.2.1.3 X-Ray image acquisition (real-time) <REQ_XFM_3>. Capture of the X-Ray fluoroscopy screen via a screen multiplier and a frame grabber card and transfer of the images captured images into XFM suite.

3.2.1.4 XF device parameters tracking <REQ_XFM_4>. Transfer of the acquisition parameters of XF instrument: PA, SA, SID, SOD, IS, Table position into XFM Suite.

3.2.1.5 MRI volume construction <REQ_XFM_5>. Acquired MRI images should be processed and an output volume which will enable segmentation of markers in MRI acquisition should be constructed with the series of MRI images.

3.2.1.6 MRI data marker segmentation <REQ_XFM_6>. Volume information acquired from MRI images should be processed with a segmentation technique to segment out the 3D locations of the markers in the scanned volume.

3.2.1.7 XF data marker Segmentation <REQ_XFM_7>. Images acquired from XF marker localization scan should be processed with a series of segmentation techniques to segment out 2D locations of the markers in each image.

3.2.1.8 XF image distortion correction <REQ_XFM_8> . 2D coordinates of the segmented markers should be corrected with the calibration data gathered to obtain distortion–free coordinates in 2D XF plane.

3.2.1.9 XF 3D reconstruction <REQ_XFM_9>. A given set of 2D coordinates gathered from a series of XF images should be processed through a back-projection algorithm and corresponding 3D point or points should be generated in XF 3D coordinate system.

3.2.1.10 3D-3D registration of point clouds <REQ_XFM_10>. Given two sets of correlated 3D points in different spaces, a registration algorithm should generate a mapping between corresponding points of the sets.

3.2.1.11 3D transform construction <REQ_XFM_11>. Given two sets of mapped 3D points, 3D transformation parameters for one of the sets should be derived with condition of minimizing 3D distance between points after transform.

3.2.1.12 3D contour generation <REQ_XFM_12>. Given a set of MRI images, this module should be able to provide user graphical interface to define 2D overlays like points, lines, circles or any desired parametric/nonparametric curve. And a set of 3D points should be generated with corresponding contour information attached.

3.2.1.13 2D contour generation <REQ_XFM_13>. Given a 2D MRI or XF Image, module should be able to provide user graphical interface to define 2D overlays like points, lines, circles or b-splines on the image. And a set of 2D points should be generated with connected image information.

3.2.1.14 Fusion of two images <REQ_XFM_14>. Given two images (one image is a stream flowing in real-time) , module should provide one fusion image as one of the images fused over another.

3.2.1.15 3D to 3D transformation <REQ_XFM_15>. Given a set of points in 3D and a 3D transform function (rotation, translation) module should calculate output 3D points after transform is performed on the given set.

3.3 Software Architecture

3.3.1 Software Requirements

3.3.1.1 Performance. Performance is one of the most important issue in software development CPU and memory usage are some criteria's for performance. In addition to these as a imaging tool our tool should meet minimum refresh rate of 15 frames per second. The limitation is determined with animal and human intervention experience by our colleague research group in National Lung Blood Institute(NHLBI) in National Institutes of Health.

3.3.1.2 Code economy. Code economy need has two main purposes: First is to use already validated codes to implement a solution therefore short-cutting approval procedures (like FDA) which is provided by XIP platform .Second is to implement software in a manner that multiple implementation of same functional code should be avoided not to enlarge the code and complicate potential changes in implementation also misguide developers who would want to learn and alter the existing system.

3.3.1.3 Ease of design. Software design decisions should be discussed in detail not to complicate implementation step and allow implementation by small pieces with precise inputs and outputs as interfaces. Also design should be easily understantood by a another developer as an introduction to the system. Response Time: Software will be running in a time critical environment a surgery room And software should handle process of the data flow from various instruments and able to process these data and provide user with output also in real-time with minimum latency.

3.3.1.4 Ease of work-flow. This requirement is specifically requested all of our clinical partners. The existing system (AngioTools toolbox written in Matlab) suffers from multiple time-consuming steps during time-critical periods of the interventional procedures. There is a need for a better integration of the new software with clinical procedure and smooth flow of the whole process.

To fulfill the requirements defined above a composite component software design is done. The architecture design can be seen in the Figure 3.1. Detailed requirement-component correspondence is discussed in detail in Appendix A.

Functional modules can be easily identified in Figure 3.1. XFM suite components are divided into two main types:

- Offline: Operations that are performed previous to the intervention once.

- Online (Real-Time): Operations responsible of handling actions (C-Arm or table movement) could be repeated through-out the intervention. There will be a need to re-render the registered surfaces from the next vantage point.

XFM Suite leads user during the procedure with the actions corresponding to the components of the work flow seen in Figure 3.2.

As shown in Figure 3.2 XFM Suite consists of various use cases covering XFM procedure and additional supporting operator actions. XFM procedure flow is the main use case chain that software is based on. Therefore, results of XFM procedure with

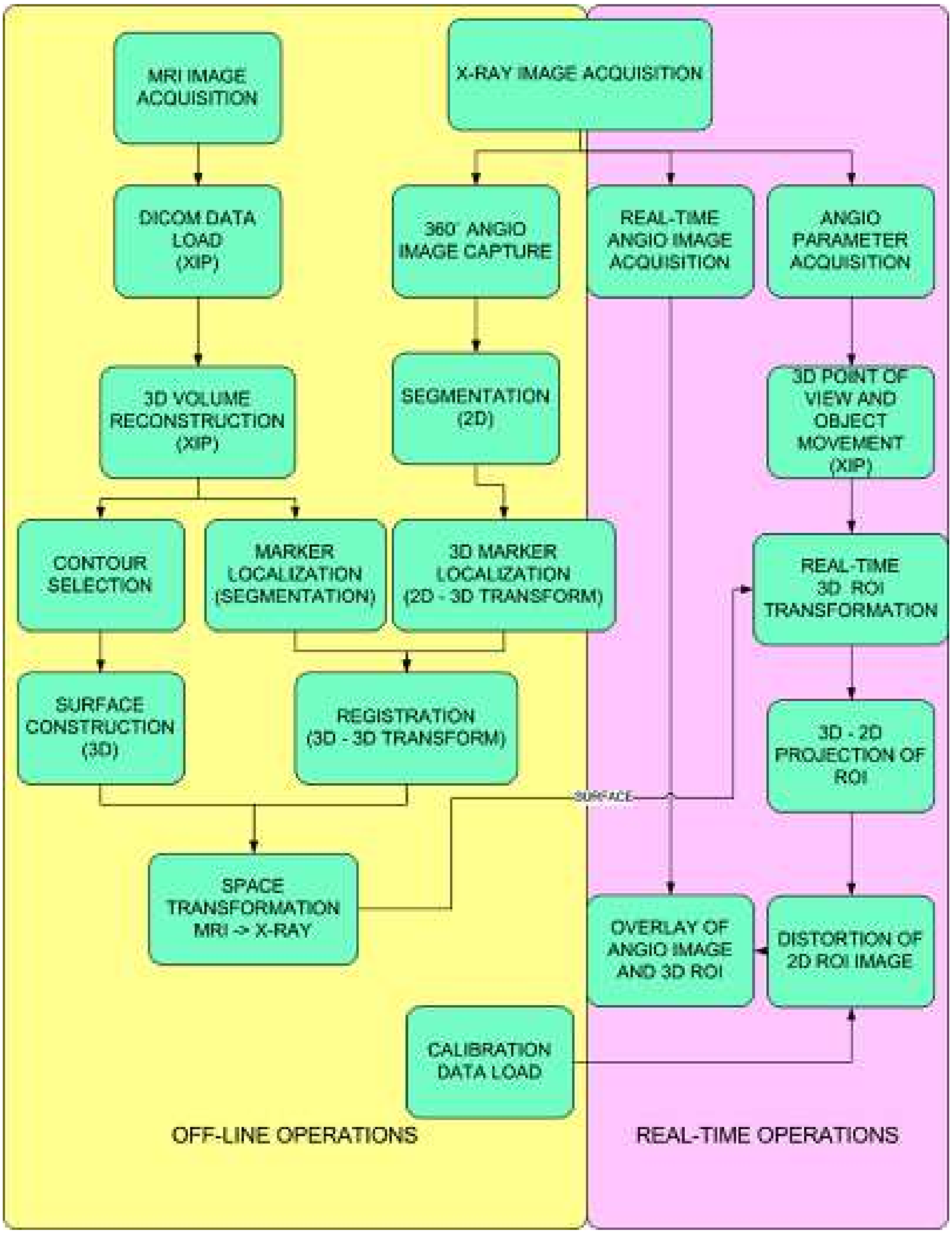

Figure 3.1 Complex Component Diagram of XFM Suite

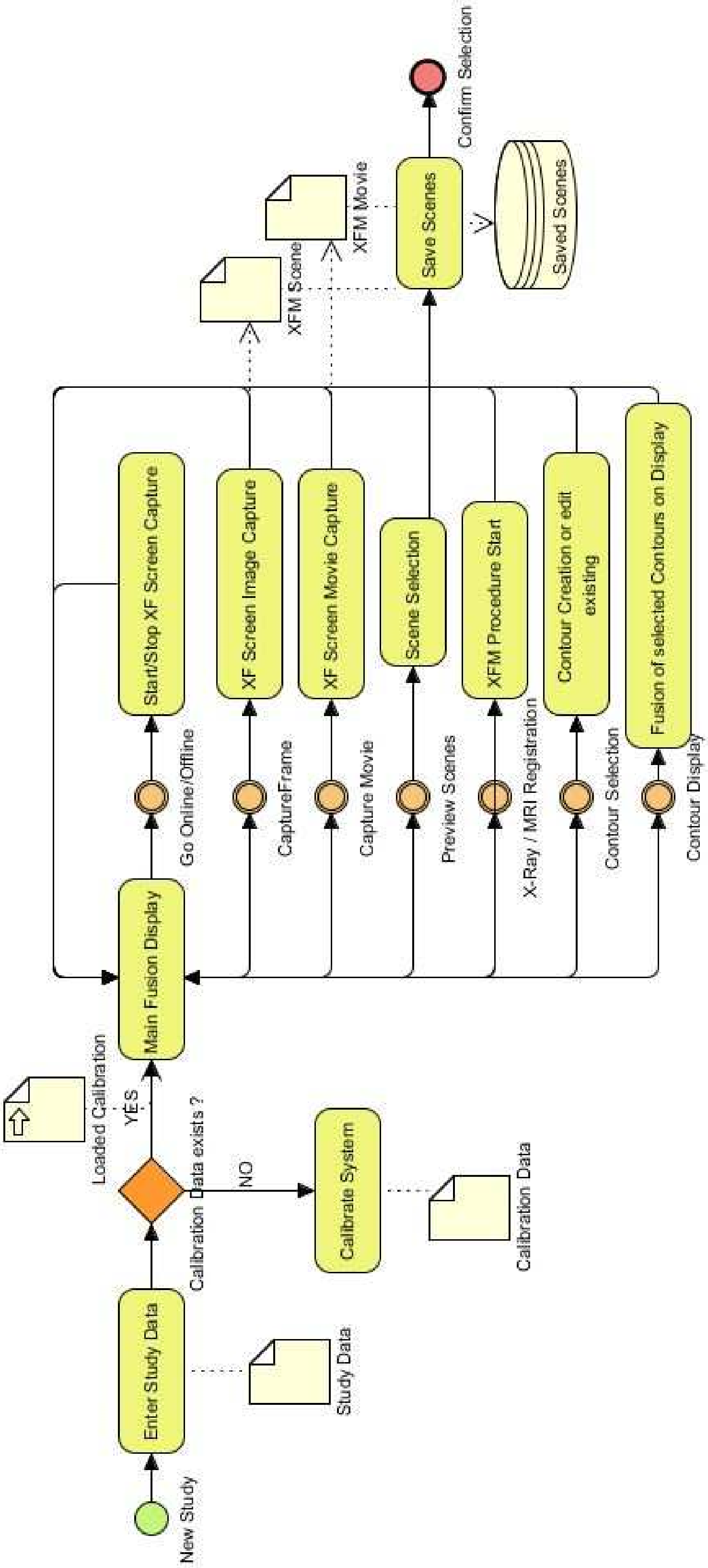

Figure 3.2 XFM Suite Flow chart

proposed software solution is discussed in detail with a demonstration in Section 3.4.

3.4 XFM Procedure Demonstration with XFM Suite

XFM demonstration starts with user trigger with button labeled as "X-Ray MRI Registration" on main XFM Suite UI screen. System guides the user with first step of XFM procedure, loading of image set of the patient with marker belt acquired from XF instrument with different PA and SA angles. Image set is in DICOM format and additional required information about image set is gathered by XFM Suite with parsing the DICOM header. Output of the process is XF images shown in UI with navigation option through the images within image set (screenshot is shown in Figure 3.3).

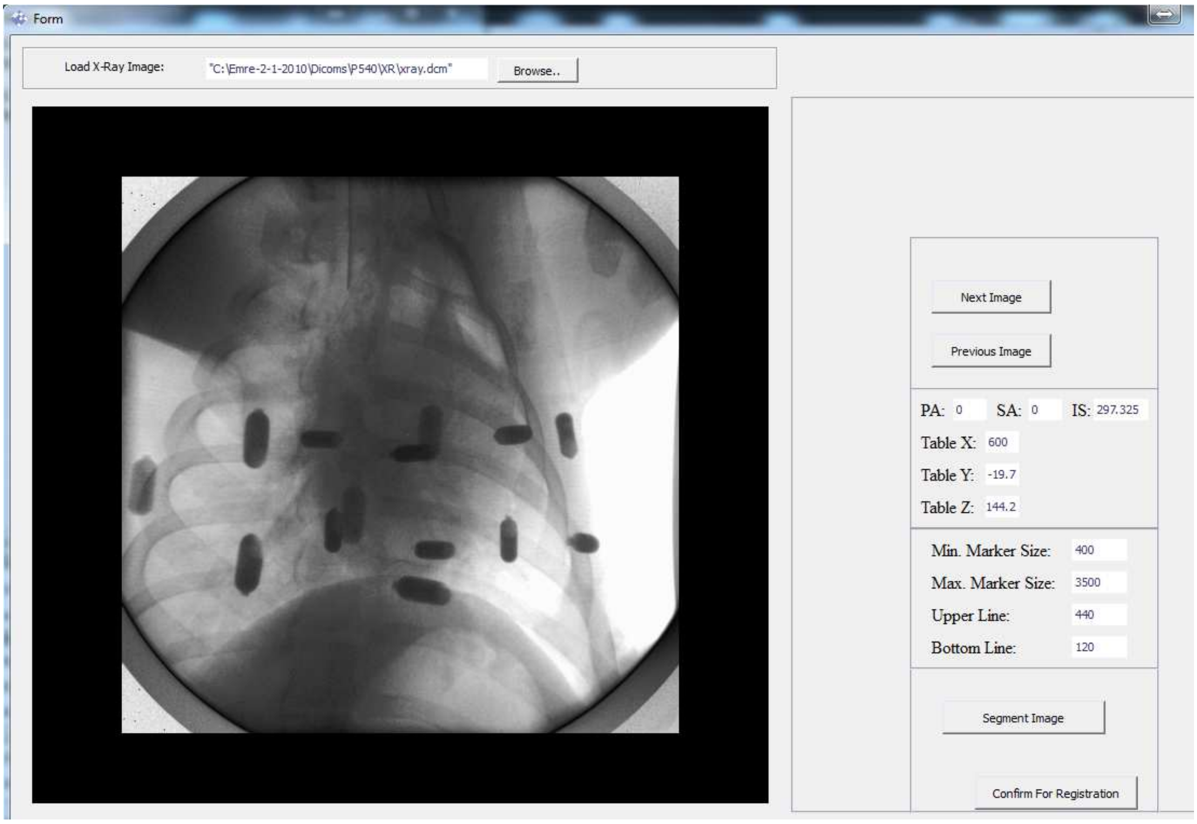

Figure 3.3 X-Ray Fluoroscopy data loading screenshot

Proceeding with XF images loaded in XFM suite system will automatically process the XF image by performing series of filters provided by ITK component of XIP which utilizes canny-edge detection, region growing, binary-thinning, smoothing recursive Gaussian filter and noise image filter. Output image is displayed in UI with parameters used for segmentation (screenshot shown in Figure 3.4). User is provided with option to change the parameters shown in UI and resegment XF images for better results and to confirm segmentation parameters for batch segmentation process with button labeled as "Confirm for Registration".

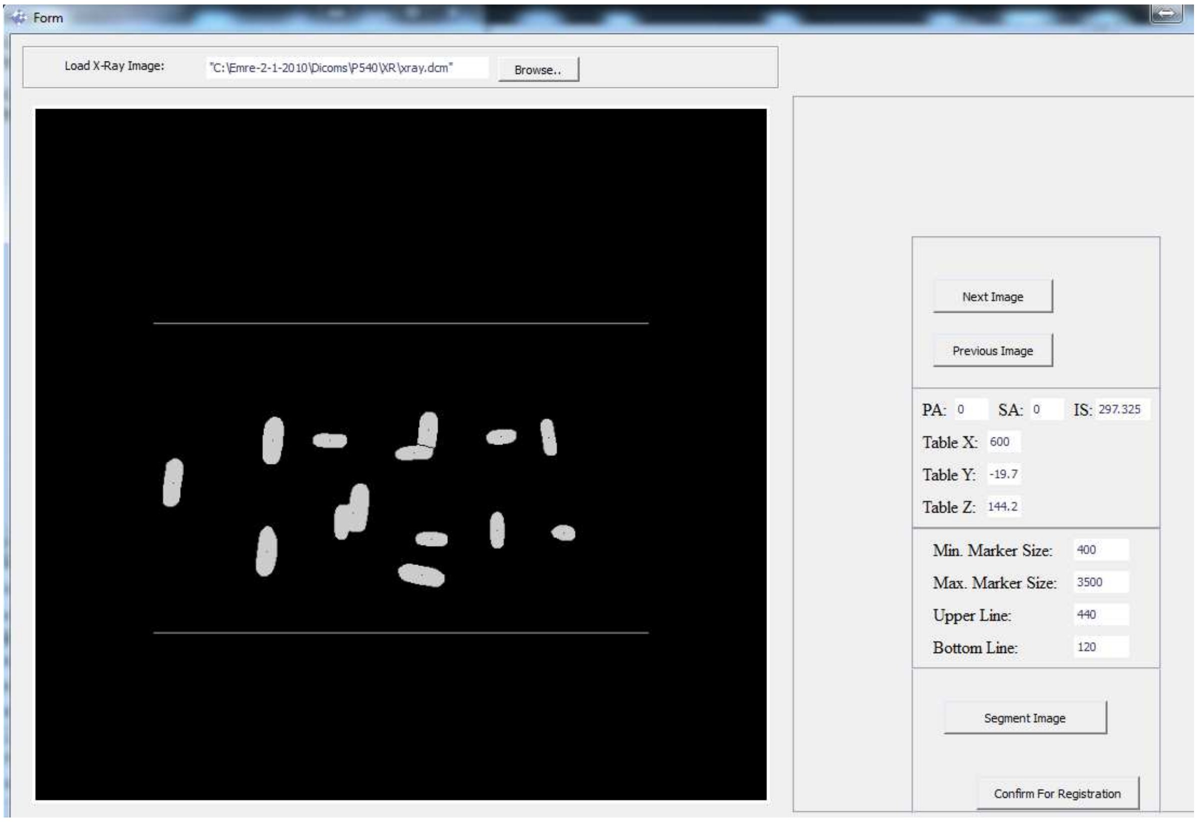

Figure 3.4 XF image segmentation screenshot

Following segmentation of fiducial markers in XF images, user is guided to loading of data acquired in marker contrast based MR scan (discussed in detail in Section 2.1.5). In this step MR images in DICOM format are loaded into XFM Suite for further processing. Output of the process is MR images displayed in UI with navigation option through the images of the scan. A screenshot of sagittal MR image in XFM Suite is shown in Figure 3.5.

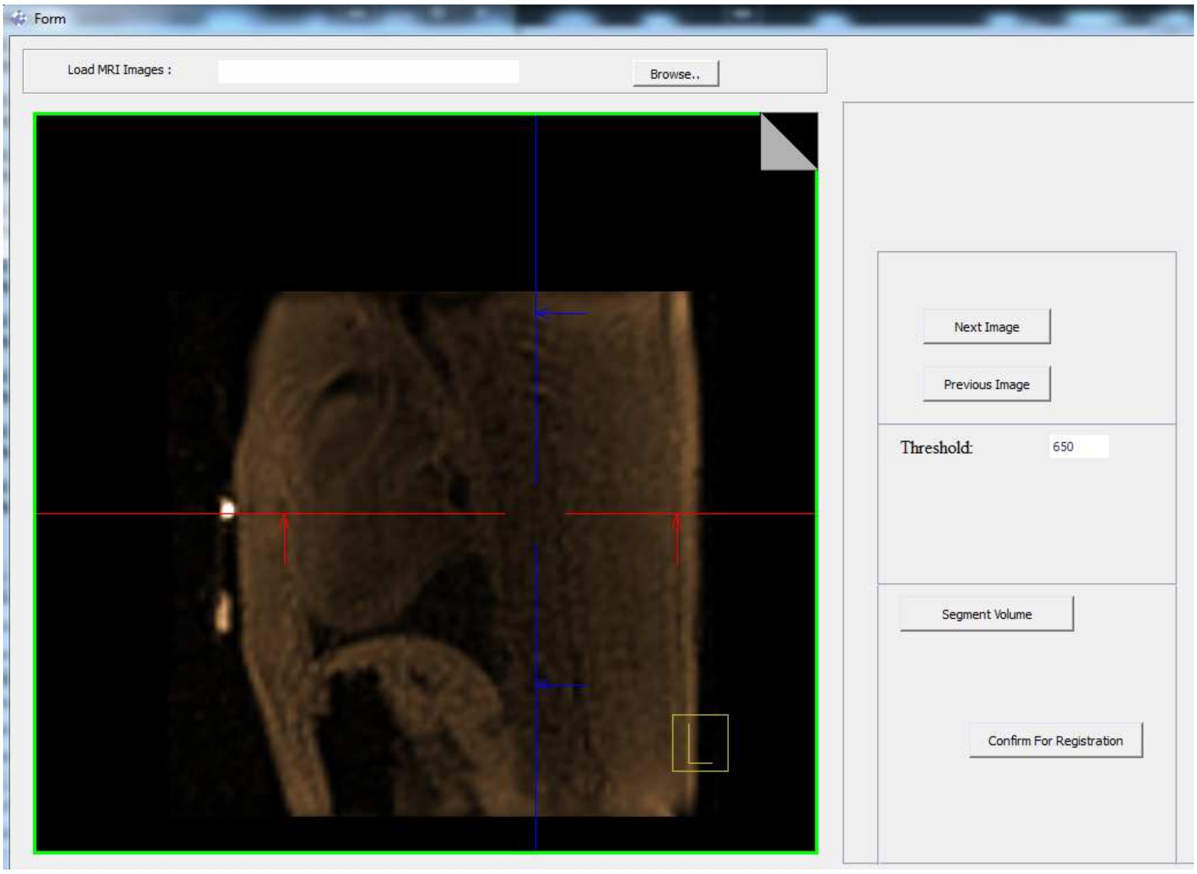

Figure 3.5 MR data loading screenshot

Succeeding MR marker localization images loaded into XFM Suite, system will form multi-planar projections of the volume constructed by MR images for user guidance. Volume that contains the markers is visualized in addition to 2D planar projections in order to validate quality of the scan data by user. A screenshot of 3D reconstruction of the MR data is shown in Figure 3.6.

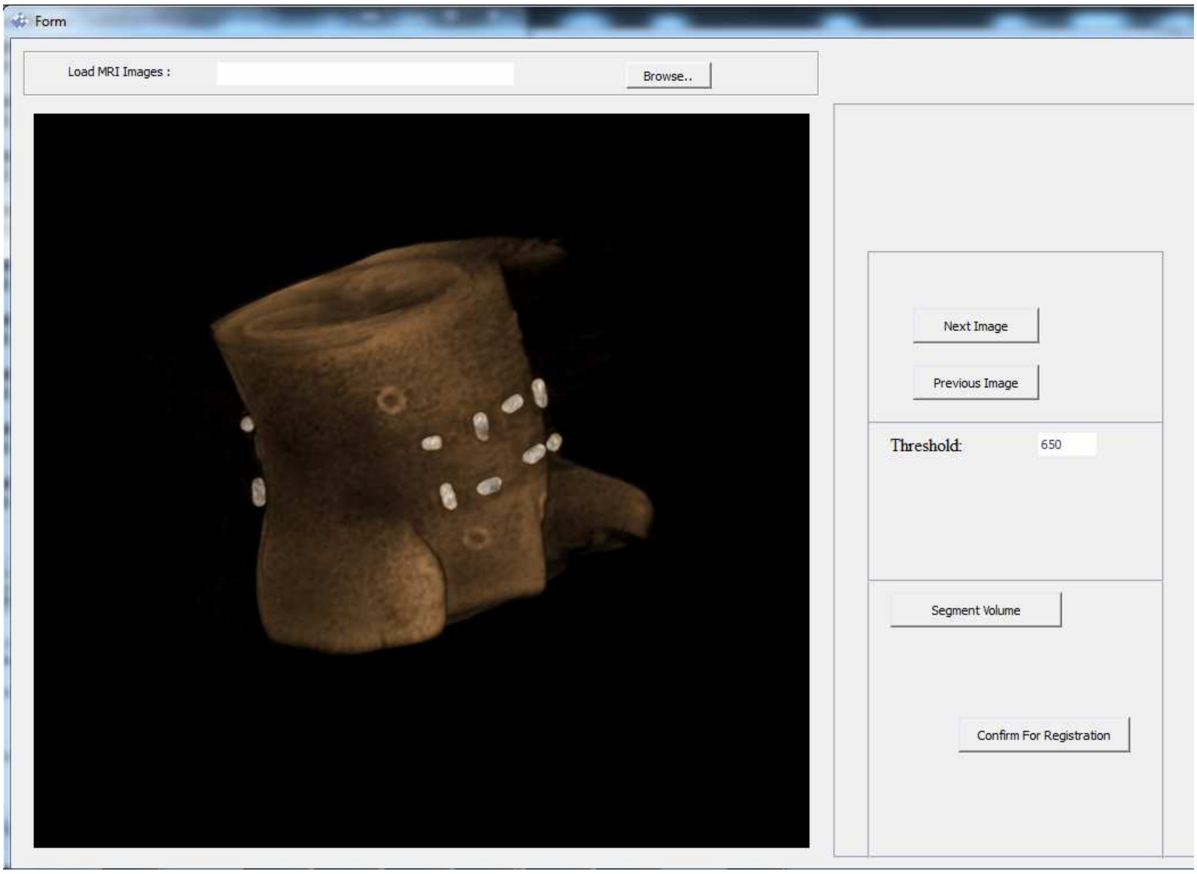

Figure 3.6 3D reconstruction of the MR marker localization scan

With validation of the marker based MR scan data, user is directed to segmentation of volume information to detect positions of the markers in 3D. By pressing the “Segment Volume” button user can segment out the marker positions according to various parameters. As the output of volume segmentation, positions of the markers are shown in 3D in UI (screenshot is shown in Figure 3.7).

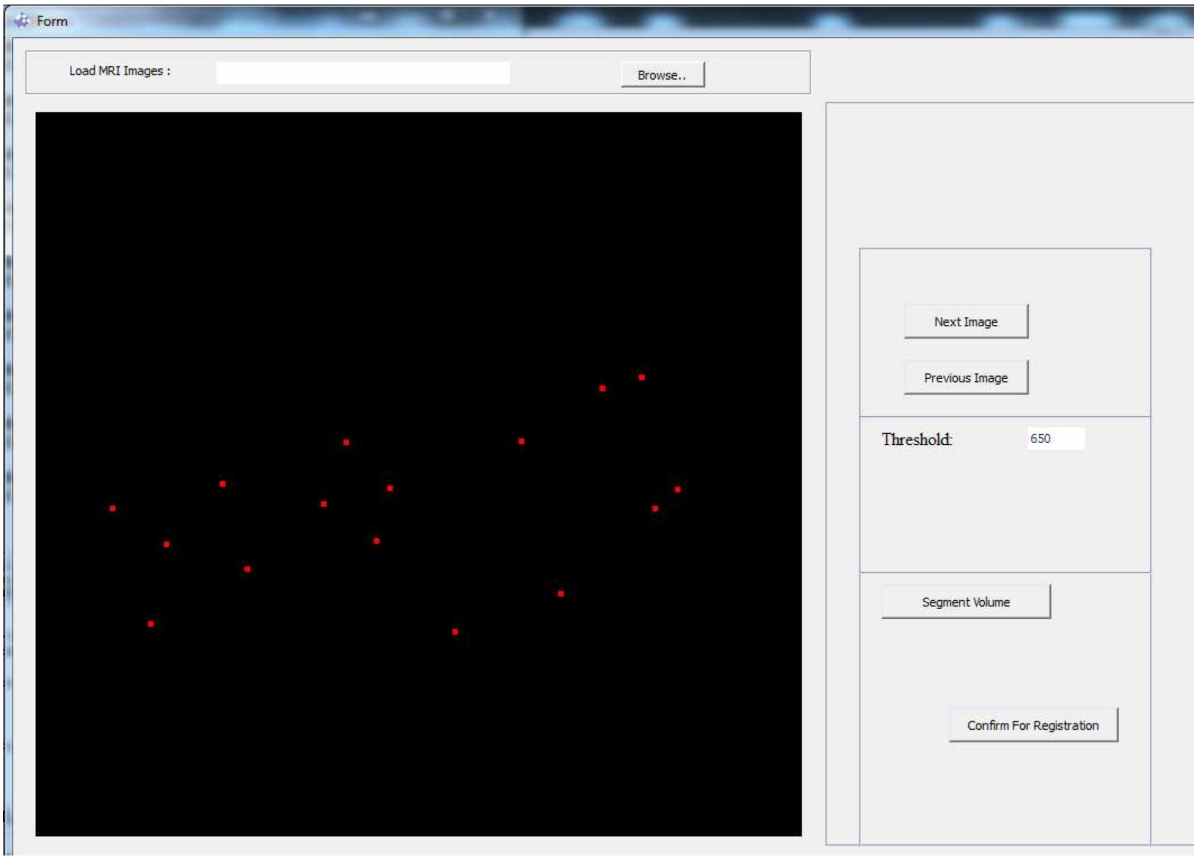

Figure 3.7 3D volume segmentation screenshot

Proceeding segmentation of markers in MRI volume data, user is leaded into registration step of XFM Suite. In the first UI scene of this section 3D MRI marker positions are shown with green spheres. Buttons in the right column of UI guides user with various steps of the registration. Reconstruction of XF marker positions in 3D is the next step of registration process. By pressing the button labeled as "Construct Source to Marker Paths" user can create the virtual paths between marker positions in XF images and the position of X-Ray source in XF space. Output of the process is visualization of the paths and unregistered MRI marker positions displayed in the same scene (screenshot is shown in Figure 3.8).

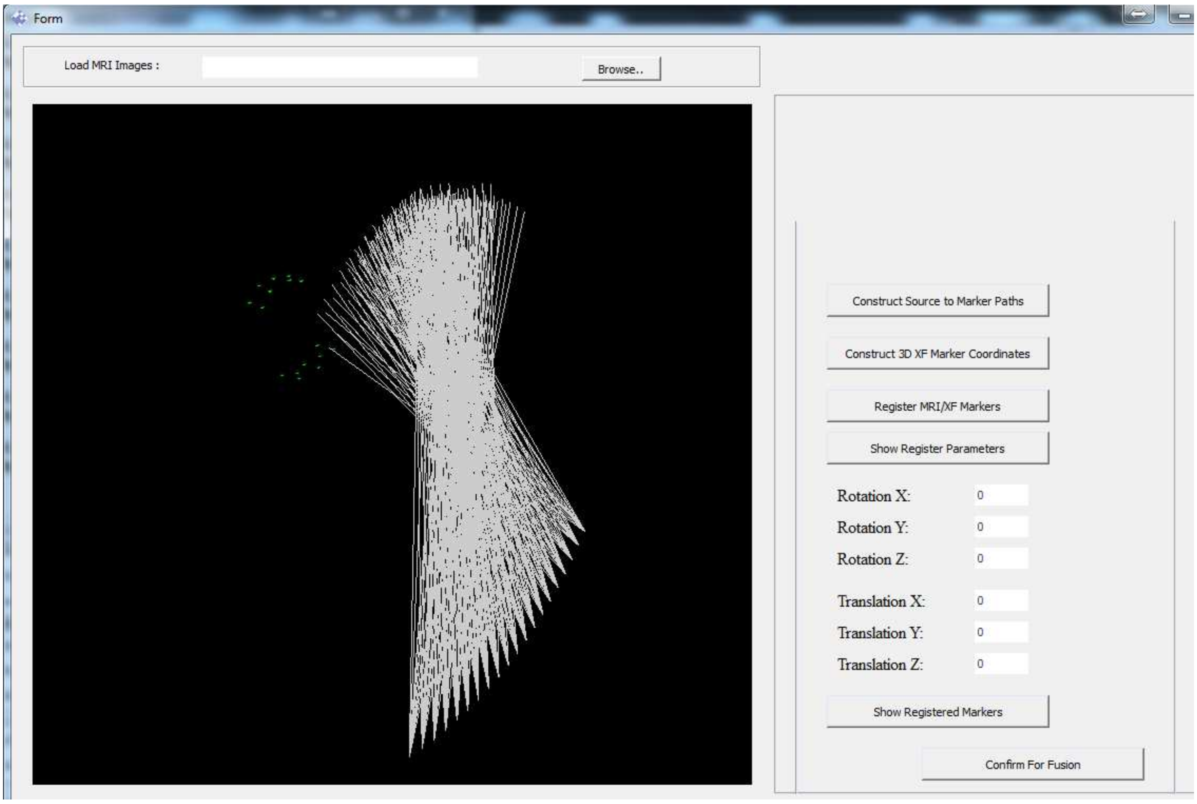

Figure 3.8 3D visualization of the virtual paths between X-Ray source and marker positions on image planes

With virtual paths between X-Ray source positions and marker positions on corresponding image planes it is possible to identify 3D positions of markers at intersection points of the virtual paths. 3D reconstruction of XF markers is triggered with button labeled as “Construct 3D XF Marker Coordinates”. Output of this process hides the virtual paths in the rendering area and adds the intersection points of the paths with red spheres presenting the XF marker coordinates in 3D instead (screenshot is shown in Figure 3.9).

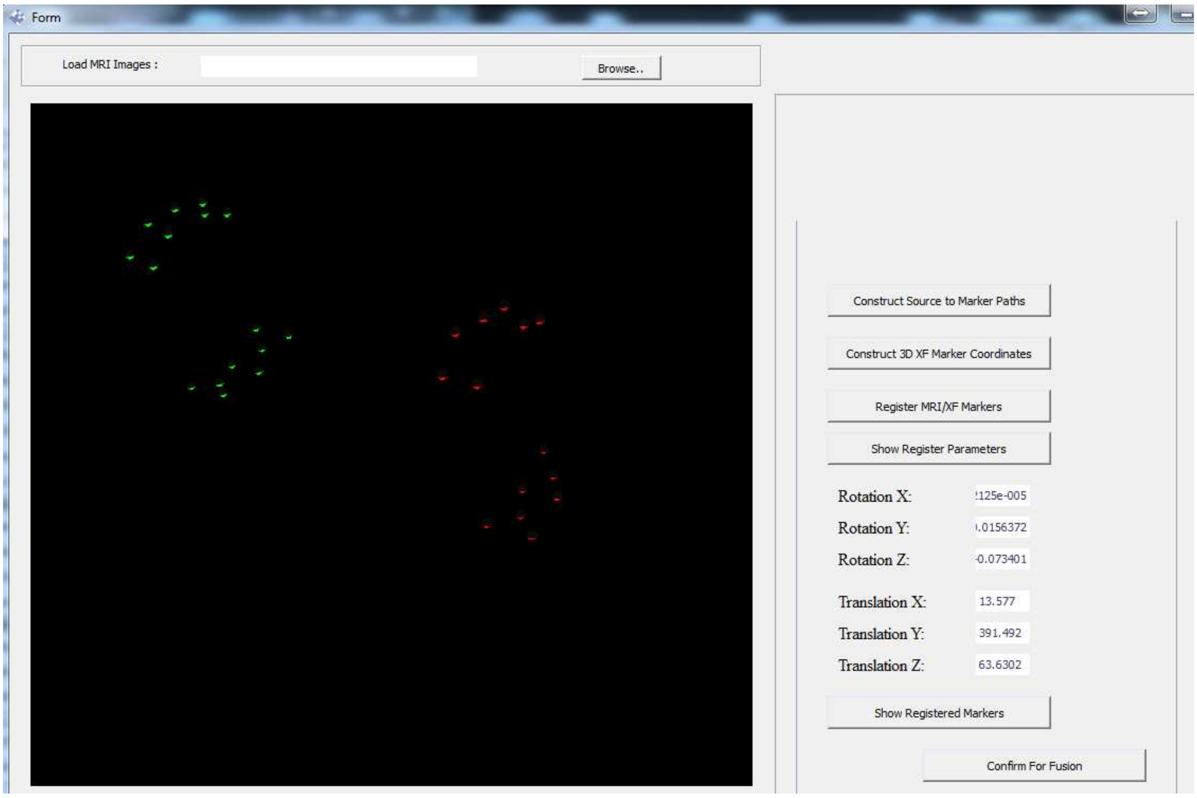

Figure 3.9 Fiducial marker coordinates in MR and XF spaces. Green spheres represent markers in MR space. Red spheres represent markers in XF space.

Identification of the marker positions in MR and XF spaces enables XFM Suite to register two point sets with point-based registration technique. Registration process is triggered with button labeled as “Register MRI/XF Markers”. Registration process provides XFM Suite the required transformation parameters between MR space and XF space. Using transformation parameters system can transfer any contour information from MR space into XF space. Marker positions in MR space transformed with registration parameters and visualized with yellow spheres. Registered MR marker positions are displayed with corresponding marker positions in XF space (represented with red spheres) in the same scene so visual validation of registration can be done by user (screenshot is shown in Figure 3.10).

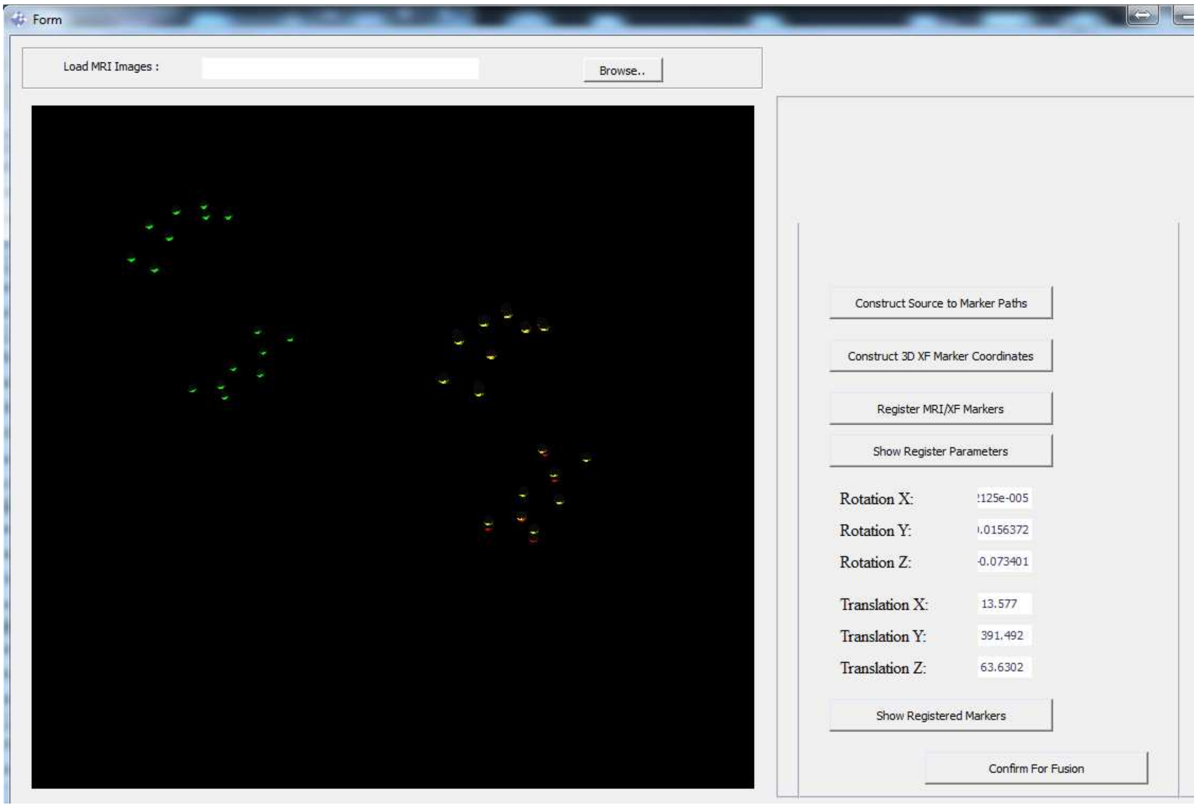

Figure 3.10 Positions of markers represented with yellow spheres identified in MR Scan after transformation into XF space

As the final step of XFM procedure, 3D information provided by the anatomic MR scan is transformed into XF space. Fusion of information coming from MR over XF screen requires adjustment of 2D projection according to XF acquisition parameters stated below:

- PA, SA, IS, SID, Table Height, Table Side, Table Longitude

2D projection construction is triggered by confirmation of the registration parameters by user with button labeled as "Confirm for Fusion". XFM Suite constructs the corresponding 2D projection according to XF tracking system and fuses the 3D data onto the XF screen captured by XF screen capture module. A simulation is provided for demonstration and validation of the process is done with DICOM image sets used for XF marker segmentation. In Figure 3.11 it can be seen that fusion of marker positions identified in MR scan and transformed with registration parameters match the marker positions in XF image.

Figure 3.11 Fusion of marker positions identified in MR images fused over XF Image

4. CONCLUSION

Implementation of XFM suite shows us that XIP platform is a good candidate for medical application development. It provides various drag and drop complex image processing modules to speed up the development. Implementation language of XIP is C++ which requires object oriented programming knowledge for potential users.

Most of the functional modules composing XFM Suite are implemented utilizing built-in functions provided by XIP platform. Custom requirements of XFM Suite are met with home-made extension modules implemented within our group. Some of the custom modules implemented can be listed as: 3D segmentation of fiducial markers in MR data, 3D reconstruction of fiducial markers from 2D coordinates, 3D-3D point based rigid registration, XF parameter tracking, XF screen capture and 2D image fusion.

Functions with necessities like matrix operations or user interface integration become the main bottle-neck of implementation in XIP platform. Shortcomings like these were eliminated with integration of various libraries to XFM Suite implementation. “Boost” library is utilized for file system operations and persistence of data structure employed in XFM Suite (discussed in detail in Appendix B). ”OpenCV” library is utilized for image export and matrix operations required in various post-process modules of XFM Suite. QT library is utilized for implementation of UI tools customized for XFM Suite. As the proposed solution in this study is a software tool validation would be done with a real-time system integration and test.

4.1 Future Work

As the current system is implemented in XIP platform it can easily be modified or extended. Considering the current status of the project; first it needs to be tested in a real interventional experiment with XF capture and XF tracker modules running. Only by testing the system in the final environment quantitative errors could be computed and final word about its feasibility and clinical validation could be stated. As an extension to this software, an integrated XF parameter identification module could be added. This would allow our current system to be used in previous XF systems without capability of broadcasting XF parameters over LAN. This integration will also avoid the dependency of our software tools to a specific XF system manufacturer. Additionally, extension of current 3D fixed surfaces with an animated 3D surface with ECG gate would increase the active registration capability and assist physician with better precision in moving organs.

Appendix A. XFM Suite Modules

A.0.1 Load DICOM Data Module

Covered Requirements

Module covers the requirements below:

1. Loading of the acquired MRI images to XFM Suite via DICOM file transfer. (<REQ_XFM_1>3.2.1.1)
2. Loading of the acquired XF marker detection images to XFM Suite via DICOM file transfer. (<REQ_XFM_2>3.2.1.2)

Covered Use Cases

Possible user actions are listed below:

1. Load XF Images
2. Load MRI Images
3. Navigate through the loaded images
   (a) Next Slice
   (b) Previous Slice
   (c) Next Image Series
   (d) Previous Image Series

Functional Description

1. Inputs

   (a) Inputs are image files in standard DICOM image format used by medical imaging instruments.

2. Outputs

   (a) SoXipMFDataDicom: A data type used in XIP platform for handling DICOM data which can be examined for defined user actions.

3. Process

   (a) Image load is performed and image examinations (next Slice, next image) are performed according to the type of input (XF or MRI) output image is shown in the user interface.

A.0.2 XF Screen Capture Module

Covered Requirements

Module covers the requirement below:

1. Capture of the X-Ray fluoroscopy screen via a screen multiplier and a frame grabber card and transfer of the images captured images into XFM suite.(<REQ_XFM_3> 3.2.1.3)

Covered Use Cases

Possible user actions are listed below:

1. Start Capture Screen: System starts real-time capture of the XF system using integrated frame grabber

2. Stop Capture Screen: System stops transferring captured XF images to the screen

Functional Description

1. Inputs
   (a) Frame grabber driver handle and a screen that can be monitored via DVI input
2. Outputs
   (a) An image with format of SoXipImage (standard image format in XIP platform) which will be shown as output image in user Interface
3. Process
   (a) Module reads the driver handle file as input. It initializes the driver and starts reading the output buffer of the frame grabber. Reformat is needed to transfer the high resolution output image to XIP system as an image. Output image can be processed or directly shown to user in UI.

A.0.3 XF Instrument Tracking Module

Covered Requirements

Module covers the requirement below:

1. Transfer of the specific parameters of XF instrument into XFM Suite employing a special program provided by manufacturer (in this study Siemens). (<REQ_XFM_4> 3.2.1.4)

Covered Use Cases

Possible user actions are listed below:

1. Start system tracking: Starts the integrated program provided in XFM suite to track the XF system for various parameters like PA, SA, SID, IS table height, table side, table long
2. Stop system tracking: Stops tracking of the instrument by XFM Suite.

Functional Description

1. Inputs
   (a) User action to start the tracking and provided system specific tracking tool integrated into XFM Suite
2. Outputs
   (a) XF system information required by XFM Suite to re-process saved contours or 3D projections. Information gathered via this module are:
   - PA: Primary angle of C-Arm orientation
   - SA: Secondary angle of C-Arm orientation
   - IS: Current intensifying screen size (110/220/330)
   - SID: X-Ray source to intensifying screen distance
   - SOD: X-Ray source to object distance
   - Table Height: Table position along ground – table axis according to predefined position
   - Table Side: Table position along patient right-patient left axis according to predefined position

- Table Long: Table position along patient head-patient foot axis according to predefined position

3. Process

   (a) With user request system starts capturing the network packages broadcasted by the XF system. Module parses these packages to corresponding XF data type and copies the requested data from gathered data type to XFM Suite module output.

A.0.4 XF Marker Segmentation Module

Covered Requirements

Module covers the requirement below:

1. Images acquired from XF marker localization scan should be processed with a series of segmentation techniques to segment out 2D locations of the markers in each image.(<REQ_XFM_7> 3.2.1.7)

Covered Use Cases

Possible user actions are listed below:

1. Segment input Image: Segmentation of the input image with current parameters is performed.
2. Change segmentation parameters: Parameters used in marker segmentation algorithm will be changed according to input.

Functional Description

1. Inputs

   (a) Input image to be segmented

   (b) Segmentation Parameters:

      i. Marker Size Minimum: Minimum marker size in pixel value to be segmented. Areas identified with less value will be ignored in the output

      ii. Marker Size Maximum: Maximum marker size in pixel value to be segmented. Identified areas with larger value will be ignored as non-marker shape or up to a percentage difference will be re processed for combined markers.

      iii. Segmentation Upper Border: For the ease of segmentation process a region can be defined with upper border as the area with larger y value than defined border will not be segmented.

      iv. Segmentation Lower Border: For the ease of segmentation process a region can be defined with upper border as the area with less y value than defined border will not be segmented. Marker Length: Definition of the circumference limitation of the markers which will be used to filter out long lines identified in the image.

2. Outputs

   (a) Output image with segmented marker areas identified as white and other regions as black

   (b) 2D center coordinates of the segmented marker regions to be processed in 3D reconstruction

3. Process

   (a) Segmentation process performs various filters to the input image like canny edge detection, Gaussian smoothing and binary thinning and then with the implemented region growing algorithm closed loops will be identified and filtered according to parameters defined by user.

A.0.5 MRI Volume Construction Module

Covered Requirements

Module covers the requirement below:

1. MRI volume construction: Acquired MRI images should be processed and an output volume which will enable segmentation of markers in MRI acquisition should be constructed with the series of MRI images.(<REQ_XFM_5> 3.2.1.5)

Covered Use Cases

Possible user action is stated below:

1. Construct MRI volume: User action will trigger various processes to form an MRI volume based on the images acquired

Functional Description

1. Inputs
   (a) Directory path including MRI images in DICOM format.
2. Outputs
   (a) MRI Volume Data which can be rendered with XIP volume rendering tools.
3. Process

- Input directory is scanned for DICOM images.
- Found DICOM images are sorted according to slice index.

- Sorted DICOM image list is processed with a volume construction algorithm and output voxel data is passed as output for rendering tool.

A.0.6 MRI Volume Segmentation Module

Covered Requirements

Module covers the requirement below:

1. MRI data marker segmentation : Volume information acquired from MRI images should be processed with a segmentation technique to segment out the 3D locations of the markers in the scanned volume.(<REQ_XFM_6> 3.2.1.6)

Covered Use Cases

Possible user action is stated below:

1. Segment MRI volume: Segmentation of voxels with higher gray-scale values is performed with a proposed algorithm. Segmented voxels correspond to MRI markers in the volume.

Functional Description

1. Inputs
   (a) Input volume: MRI volume data to be segmented.
   (b) Input size: Input size ratio used in adapted segmentation algorithm.
   (c) Threshold: Voxel gray-scale threshold value to be used in segmentation process.

2. Outputs

   (a) Marker coordinates: Segmented marker coordinates in MRI space as a point set.

3. Process

   (a) Input volume data is processed thorough with threshold value eliminating the voxels with less gray-scale values. Qualified voxel coordinates are passed to a region growing function to determine marker volume limits and linked voxels are labeled with marker index. All determined marker volumes are processed for center of volumes. Results are copied to the output as a 3D coordinate array.

A.0.7 XF Distortion Correction Module

Covered Requirements

Module covers the requirement below:

1. XF Image distortion correction: 2D coordinates of the segmented markers should be corrected with the calibration data gathered to obtain distortion–free coordinates in 2D XF plane.(<REQ_XFM_8> 3.2.1.8)

Covered Use Cases

Possible user actions are listed below:

1. Calculate distortion coefficients: User action triggers a folder scan for a series of DICOM images. Listed images are processed with a distortion detection algorithm to calculate a distortion polynomial model.

2. Correct distortion: User action triggers a function accepts calculated polynomial coefficients and 2D image coordinates as inputs and outputs corrected 2D coordinates.
3. Distort image: User action triggers a function which transforms an image without distortion into a distorted one with distortion coefficients. This is required for fusion of distortion free 3D contour data on to distorted XF screen capture.

Functional Description

1. Inputs
   (a) Distorted image series: A series of DICOM images with distortion of special calibration phantom for calibration process.
   (b) Image to be distorted: An image produced in XFM Suite in distortion free 3D space to be distorted for the fusion on XF screen.
2. Outputs
   (a) Distortion coefficients: A series of coefficients defining fitting polynomial function to formulate distortion on XF images.
   (b) Distorted image: An image formed with the original image pixel values but coordinates of pixels are reformed according to the distortion polynomial function.
3. Process
   (a) Input calibration image series consists of DICOM images of a calibration phantom designed with metal rings on a sheet of plastic (shown in Figure **2.6**).
   (b) Series is processed to form an image list with corresponding instrument parameters attached to each image like PA, SA, IS and SID. Attached parameters will be used in the following functions to form a distortion parameters array mapped to the instrument parameters.

(c) Each image in the formed list is processed first with a segmentation function to determine each metal ring position on the image. Segmented positions of the grids are processed with a proposed distortion detection algorithm to calculate non distorted ideal grid positions. Subsequently a 5th degree fitting polynomial is calculated to fit distorted 2D coordinates to 3D ideal grid coordinates.

(d) Calculated polynomial coefficients are saved with a list of instrument parameters acquired from DICOM header. This process will produce a list of coefficients with corresponding PA, SA, IS and SID values. A reverse list is also produced with ideal coordinates and distorted coordinates swapped for polynomial calculation. Resulting list of coefficients forms a transformation function of a distorted image to a corrected one and visa versa.

A.0.8 XF 3D Reconstruction Module

Covered Requirements

Module covers the requirement below:

1. XF 3D Reconstruction: A given set of 2D coordinates gathered from a series of XF images should be processed through a back-projection algorithm and corresponding 3D point or points should be generated in XF 3D coordinate system.(<REQ_XFM_9> 3.2.1.9)

Covered Use Cases

Possible user actions are listed below:

1. Reconstruct points in 3D: User action will trigger a function accepts 2D coordinates with corresponding image information like PA, SA, SID and SOD to

reconstruct a 3D projection of given 2D coordinates.

Functional Description

1. Inputs
   (a) 2D coordinate list: List of 2D coordinates with 3rd dimension attached as PA and SA values.
   (b) Acquisition parameters: Instrument parameters that are used to form transform of 2D coordinates into 3D listed below:
      i. SID
      ii. SOD
      iii. PA Increments
2. Outputs
   (a) 3D projection coordinates: List of reconstructed 3D projections of 2D coordinates.
3. Process
   (a) Reconstruction process consists of two main functions. First function acquires 2D coordinates in an image with corresponding PA and SA values and forms a line between 3D projection of 2D coordinate and the corresponding X-Ray source position. This process requires additional information about whole acquisition, SID and SOD. 2nd function process the lines constructed in 3D to form determine lines intersect or lines tangent to each other in 3D. The intersection points are filtered out with a minimum intersection number to eliminate accidental intersections between lines correspond to different markers. Qualified points are grouped with least-square method to form center of gravity 3D coordinates for each reconstructed marker. Outcome is copied to output.

A.0.9 3D-3D Registration Module

Covered Requirements

Module covers the requirement below:

1. 3D-3D registration of two point clouds: Given two sets of correlated 3D points in different spaces, a registration algorithm should generate a mapping between corresponding points of the sets.(<REQ_XFM_10> 3.2.1.10)

Covered Use Cases

Possible user actions are listed below:

1. Register 3D points: User action triggers a function which will accept two groups of 3D points and finds the correspondence between points of two sets.

Functional Description

1. Inputs
   (a) Two list of 3D points: Point groups to be registered.
2. Outputs
   (a) List of points from two sets in the same order according to correspondence between points.
3. Process
   (a) Process includes an algorithm introduced by Sönmez et.al. in his masters thesis[7] finding correspondence of two point clouds with a triangle edge similarity matching theorem.

A.0.10 XF to MRI Transform Construction Module

Covered Requirements

Module covers the requirement below:

1. 3D transform from MRI space to XF space construction: Given two sets of mapped 3D points, 3D transformation parameters for one of the sets should be derived with condition of minimizing 3D distance between points after transform.(<REQ_XFM_11> 3.2.1.11)

Covered Use Cases

Possible user actions are listed below:

1. Construct transform parameters: User action trigger a function which accepts two point sets as input. Performs a transformation calculation between corresponding sets minimizing the distance between points of the first set and transformed points of the second set.

Functional Description

1. Inputs
    (a) Two 3D coordinate arrays: Arrays holding coordinates of two lists of points with the same order according to correspondence between points.
2. Outputs
    (a) Transformation parameters: The parameters required to transform MRI space to XF space. Required parameters are listed below:

i. Rotation angle around X axis
ii. Rotation angle around Y axis
iii. Rotation angle around Z axis
iv. Translation in X axis
v. Translation in Y axis
vi. Translation in Z axis

3. Process

(a) Two input sets are processed with an algorithm to form connected 3 vectors in each set and proposed with an algorithm of 3D best fit proposed by G.H Golub et. al [49]

A.0.11 3D Contour Construction Module

Covered Requirements

Module covers the requirement below:

1. 3D contour generation: Given a set of MRI images module should be able to provide user graphical interface to define 2D overlays like points, lines, circles or b-splines. And a set of 3D points should be generated with corresponding contour information attached.(<REQ_XFM_12> 3.2.1.12)

Covered Use Cases

Possible user actions are listed below:

1. Construct 3D contour: User action triggers a function that accepts 2D point set within an MRI image with DICOM header information to form a corresponding 3D point set in MRI space.

Functional Description

1. Inputs
   (a) 2D contour Points: User defined 2D points forming different types of contours stated below on MRI slices:
      i. Line
      ii. Point
      iii. B-splines
   (b) DICOM header: Image header information that will be used in reconstruction of 2D points in 3D MRI space like slice thickness.
2. Outputs
   (a) 3D contour Points: 3D point sets in MRI space generated by the module corresponding to 2D input points.
3. Process
   (a) User request will trigger an editing mode for contour selection on MRI slice display. In selection mode, various contour types can be formed by user. Possible types are listed below:
      i. Point
      ii. Line
      iii. B-Spline
   (b) After selection creation of contours user can select to transfer the drawn contours to 3D space. System creates a corresponding 3D point set in MRI space and can display it in MRI space in 3D.

A.0.12 2D Contour Construction Module

Covered Requirements

Module covers the requirement below:

1. 2D contour generation: Given a 2D MRI or XF Image, module should be able to provide user graphical interface to define 2D overlays like points, lines, circles or b-splines on the image. And a set of 2D points should be generated with connected image information.(<REQ_XFM_13> 3.2.1.13)

Covered Use Cases

Possible user actions are listed below:

1. Create 2D Contour: User action triggers a function enables pick action on 2D XF or MRI Images.
2. Save Contour: User action triggers a function to save the created contours on defined images.
3. Load Contour: User action triggers a function to load a saved contour set over a set of images.
4. Reset Contours: User action triggers a function to clear all created contours in image set.

Functional Description

1. Inputs
   (a) Displayed image set on current display mode: Image set already loaded in a display module (XF or MRI)
   (b) Selected Contours: A set of points created by user over an image or a set of images loaded on the current display.
   (c) Saved Contours: A file contains contour information of a selected image set.

2. Outputs

   (a) Contour level displayed over the images: The created or loaded contours are displayed over the corresponding images.

   (b) Saved contours file: Contour data created by user that are not saved yet are dumped into a file with a defined format to be loaded in the future by user.

3. Process

   (a) On display mode of an XF or an MRI image user action can enable the contour creation mode. In contour selection mode user can pick points over the displayed image which will form various types of contours like points, lines or b-splines. User can navigate between slices of the image set. Selected contours will be temporarily saved during navigation period. After selection of contours user can save the defined contours with corresponding action to a file with specific format. With user action a saved contour file can be loaded back to correct corresponding image set.

A.0.13 Fusion Module

Covered Requirements

Module covers the requirement below:

1. Fusion of two images: Given 2 images flowing in real-time, module should provide one fusion image as one of the images fused over another in real-time.(<REQ_XFM_14> 3.2.1.14)

Covered Use Cases

Possible user action is stated below:

1. Fuse MR information over XF screen: User action triggers a function that will merge the image from 3D space rendering over XF 2D image capture.

Functional Description

1. Inputs
   (a) Two images to be fused. In this context it images are 2D projection of MR contours and XF screen capture images.
2. Outputs
   (a) Merged image formed by two images fused over each other.
3. Process
   (a) Module has a screen capture function capturing the 2D projection of MRI contours according to the point of view and view angle configurations depending on instrument parameters PA, SA, IS SID. Captured 2D projections are merged over a real-time captured image of XF screen.

A.0.14 3D-3D Transformation Module

Covered Requirements

Module covers the requirement below:

1. 3D – 3D transformation between XF and MRI spaces: Given a set of points in 3D and a 3D transform function (rotation, translation) module should calculate output 3D points after transform is performed on the given set.(<REQ_XFM_15> 3.2.1.15)

Covered Use Cases

Possible user action is stated below:

1. Transform MRI data into XF space: User action triggers a function that accepts 3D point set in MRI space and transformation parameters provided by XF to MRI transform construction module. Module forms corresponding point set in XF space after transform is performed with given parameters.

Functional Description

1. Inputs
   (a) 3D point set in MRI space: Input points defining contours in MRI space provided by user in contour selection.
   (b) Transformation parameters: Parameters used to perform the transformation from MRI space into XF space defined in detail in Section A.0.10.
2. Outputs
   (a) 3D point set in XF space: Output points formed by transformation of input point set with according to parameters given.
3. Process
   (a) Given points are processed with 3D rotations along X, Y and Z axis with defined angles in parameters. Output points are translated in 3D with translation parameters. Consequently formed 3D points are copied to the output.

Appendix B. XFM Suite Data Structure

XFM Suite requires a data structure to store data constructed by various modules of the suite and provide mutual access of required data by corresponding modules in run-time. Data structure forms data types linked with various modules and the relations between the data types. Figure B.1 shows the general structure.

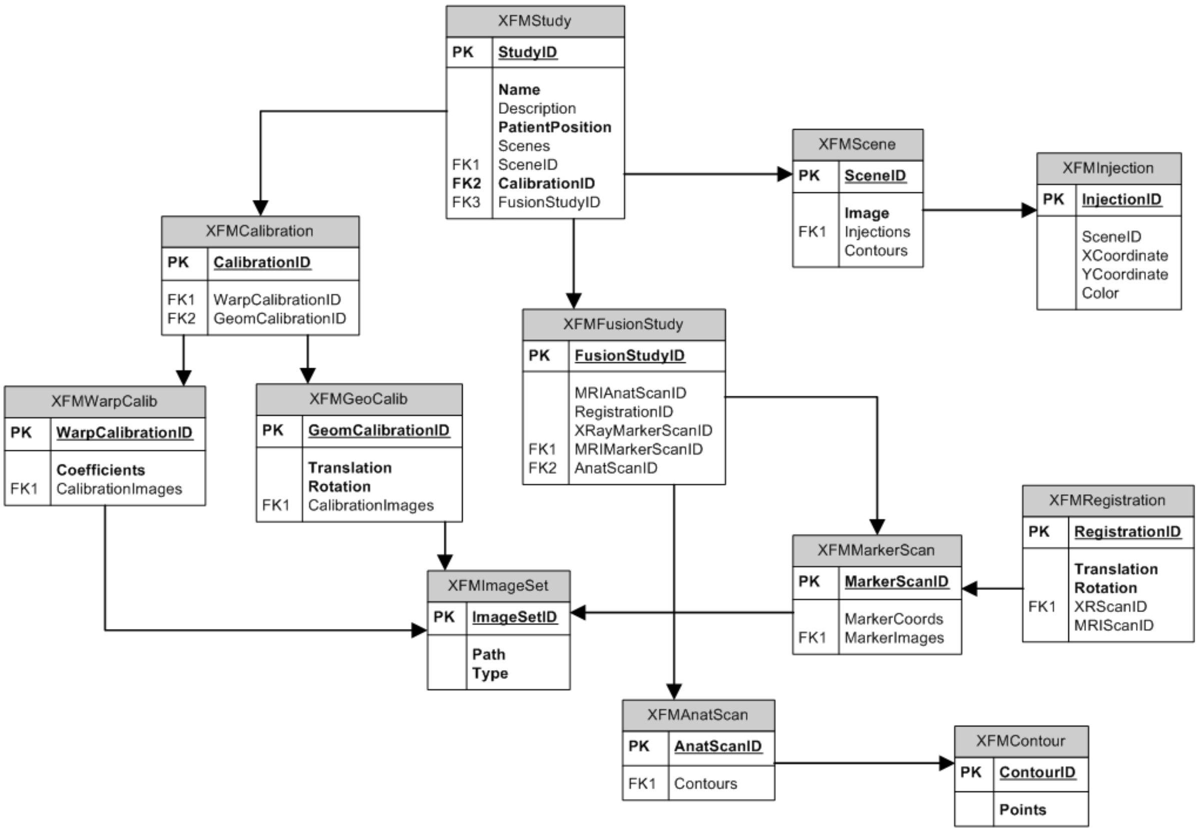

Figure B.1 XFM Suite Data Structure

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