**Thesis for Master's Degree**

# Design and Evaluation of Haptic Virtual Fixtures for Robot Assisted Cardiac Intervention

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# Design and Evaluation of Virtual Fixtures for Robot Assisted Cardiac Intervention

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# Abstract

The goal of using robots in medical area is to provide improved diagnostic abilities, a lesser invasive and more comfortable experience for the patient, and the ability to do smaller and more precise interventions. In particular, teleoperated robot assisted surgery is of huge interest as it enhances surgeon's dexterity particularly during Minimally Invasive Surgery (MIS) procedures when surgeon loses direct sight of organ and eye-hand coordination. In the meantime, incorporating haptics in telerobotics drastically increases surgeon's understanding about the current situation of surgical procedure. Haptics, which is derived from a Greek word 'haptesthai' meaning 'touch', is a process that can provide feedback, in this case the information about current surgical process, through kinesthetic or tactile display. Haptic display system is composed of input and output devices which is actually a master robot in case of telerobotics. Haptics, therefore, has been a necessary and significant research area in medical robotics.

In this work, a haptic guidance method is developed in a master-slave robotic surgical system for guidewire navigation during robot assisted coronary intervention. Since positioning the guidewire at target location is necessary in angioplasty for the stent to be permanently placed in order to widen open the blocked arteries, the proposed method aims to develop a haptics rendering algorithm directly from the currently available cardiac 2D X-ray images for localizing guidewire at target location. The most important feature of proposed method is that it doesn't require expensive and time consuming preoperative procedures to be done to make it compatible with conventional C-arm X-ray machines based procedures.

During coronary intervention procedures cardiologists frequently acquire angiograms which are high contrast images to visualize coronary arteries by injecting contrast enhancement medium, which are otherwise not visible to X-rays. In this study, single static angiogram is being used to correlate the guidewire in fluoroscopic images with vasculature in angiogram. The proposed haptic rendering depends upon the guidewire position and orientation with respect to virtual fixtures. These virtual fixtures are generated on to this angiogram over the blood vessels by mouse click and drag and actually specify the path to the desired location. If the guidewire is entering in undesired coronary vessel or to make sure guidewire enters in the target coronary vessel, haptics guidance comes into action to assist operator finish the task easily. Each fluoroscopic image, which is containing guidewire and bones (which are dense structures), is being processed by image processing module of PC program in real time, to segment guidewire and finally compute (a) guidewire tip position and (b) guidewire tip bend angle in the X-ray image. This tip bend actually correlates with the tip orientation in 3D. With the information available from the image processing and virtual fixtures, it is possible to render haptic feedback on to the master device. Aim is to align the guidewire tip bend in 2D image according to the VF vector. Each virtual fixture acts both as forbidden region virtual fixture and guidance virtual fixture under different conditions, thus ensuring better guidance to the operator. The proposed haptic rendering methodology was also evaluated by using phantom experiments, in which subjects had to navigate guidewire to the target location meanwhile task completion time was measured. Statistical analysis shows that adding haptic feedback permits users to perform task faster than conventional method, approximately 40% decrease in the task completion time was recorded for the phantom heart model environment.

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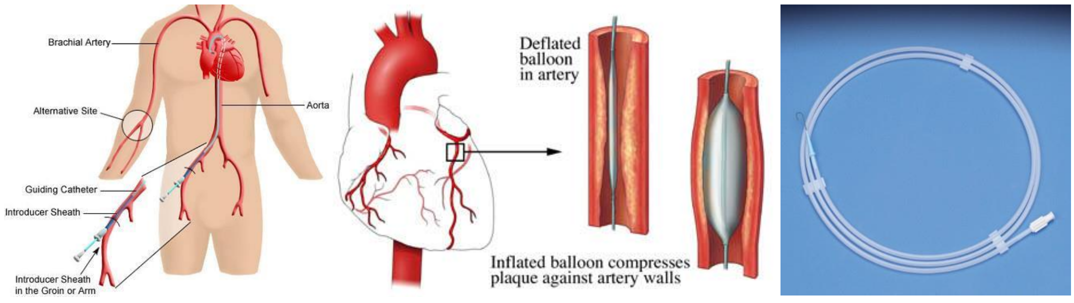
# 1. Introduction

## 1.1 Background

Coronary arteries supply blood, nutrients, and oxygen to the heart so that it can function properly. If the substance known as plaque, builds up along these arteries, they become narrow and hardened, restricting blood flow. To cure the patient, a process called coronary angioplasty is performed. Before conducting coronary angioplasty, an angiogram which is an invasive test, is performed to look for narrow or blocked blood vessels. This procedure is performed under light sedation and local anesthesia. The test includes visualizing the coronary vessels through different acquisition techniques e.g. X-ray, MRI or CT. Cardiologist may proceed to perform angioplasty and stenting upon examining the severity of blockage.

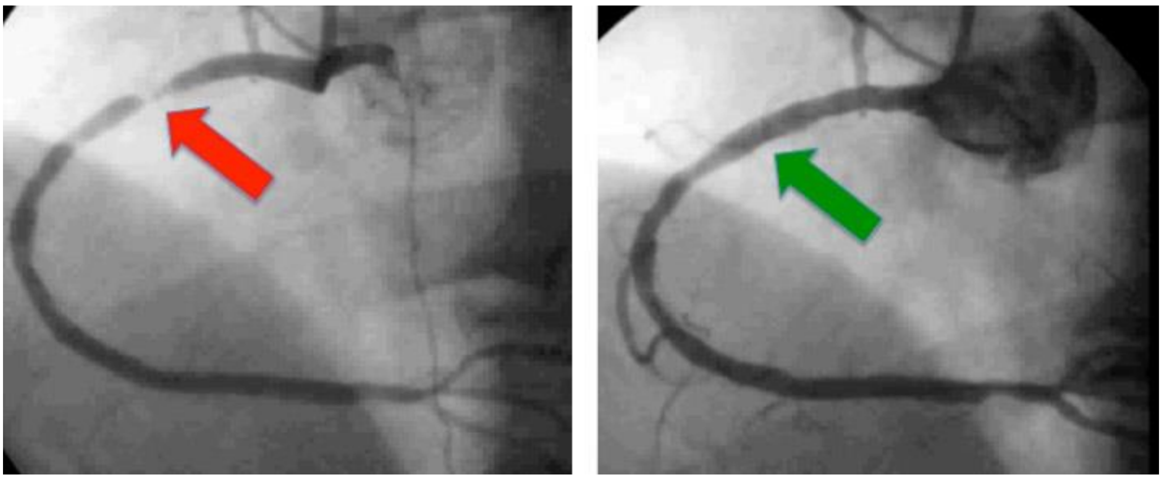
The term 'angioplasty' means using a balloon to stretch open a narrowed or blocked artery. Coronary angioplasty is relatively safe, minimally invasive procedure that is used to unblock clogged arteries. However, most modern angioplasty procedures also involve inserting a short wire-mesh tube, called a stent, into the artery during the procedure. The stent is left in place permanently to allow blood to flow more freely. Coronary




(a) (b) (c)

Figure 1-1 (a) Catheter insertion either from femoral artery (groin) or from brachial artery (arm), (b) Deflated balloon is inflated, (c) Guidewire angioplasty is sometimes known as percutaneous transluminal coronary angioplasty (PTCA). The combination of coronary angioplasty with stenting is usually referred to as percutaneous coronary intervention (PCI). A coronary angioplasty is performed using local anesthetic, which means patient is awake while the procedure is carried out [1].

Figure 1-2 shows the angiograph before and after angioplasty. On the left image artery is dangerously narrowed and needs angioplasty. In the coronary angioplasty procedure, an incision is made in the femoral artery or radial artery Figure 1-1 (a), through which catheter which is a thin tube, is inserted and guided to the affected coronary artery using an X-ray video. When the catheter is in place a thin wire, called guidewire Figure 1-1 (c), is guided down the length of the affected coronary artery, delivering a small balloon to the blocked section of artery. Cardiologist uses a handle at the proximal end of tool for guidewire and catheter manipulation, Figure 1-3 (b). To make the arteries visible in X-ray, which are invisible otherwise, a contrast medium is injected when required, to keep track of guidewire with respect to arteries. The small balloon is then inflated to widen the artery, squashing fatty deposits against the artery wall so blood can flow through it more freely when the deflated balloon is removed Figure 1-1 (b). If the stent is being used, this will be around the balloon and will be left permanently to resume the free blood flow. The stent will expand when the balloon is inflated and remains in place when the balloon is deflated and removed. Figure 1-2 (b) shows the angiograph after stent placement.

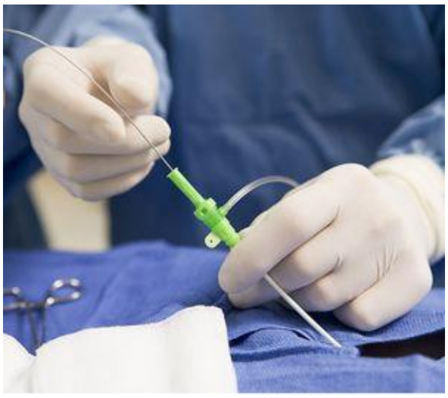


(a) (b)

Figure 1-2 Coronary angiogram, (a) Severe narrowing of artery, (b) After angioplasty and stent placement

In the operation theater, patient is laying on bed and surgeon is standing by the bed. It is necessary for the patient to be exposed to X-rays and due to the requirement of procedure surgeon is also exposed. This configuration is dangerous for the surgeons as they carry out hundreds of angioplasty surgeries throughout their carriers. Cardiologists, without robot assistance, use their hands for catheter and guidewire manipulation. A handle is available at the distal end of the tools for manipulation. Tools, which are catheter and guidewire, are being manipulated using this handle with two degrees of freedom (DOF) available named translation and twist to manipulate the guidewire and catheter. Before the procedure guidewire tip is appropriately bend according to vasculature structure and then these DOFs allow surgeons to navigate guidewire inside vasculature which is actually 3D. Since in minimally invasive procedure surgeons lose direct sight to the heart, therefore surgeons navigating guidewire towards the target location by mapping guidewire in fluoroscopic images with vasculature in angiograph. Once guidewire is reached at target location, then stenting is performed. Finally, guidewire and catheter are pulled out of body and this completes the angioplasty.

(a)



(b)

Figure 1-3 Operation theater environment, (a) C-arm X-ray machine, (b) Catheter and guidewire manipulation

## 1.2 Literature review

Recent developments in robot technology has led to many Minimally Invasive Surgical (MIS) procedures [2], e.g. cardiac intervention. It is needed for the people suffering from cardiac accidents e.g. every 43 seconds, someone in the United States has a coronary event [3]. Robot assistance in this regard can play an important role because of MIS nature of surgery. In particular, tele-robotics in the robot assisted coronary intervention has potential to greatly assist cardiologists performing the intervention task. This assistance may increase dexterity of surgeon and also haptic guidance can also be provided.

Benefits of haptics in coronary intervention, which is a Minimally Invasive Surgery (MIS), are openly acknowledged by several research groups [4-6] and many of the companies are developing equipment in this field (Hansen Medical [7] and Mentice [8], for example). Providing appropriate feedback in the tele-operated surgery system can reduce human errors and/or significantly decrease the overall surgery time through more immersive attention of the surgeon. Since providing haptic feedback will certainly decrease surgeon's effort resulting in decrease in task completion time therefore development of effective and efficient haptic feedback system becomes vital. A haptic feedback system includes not only design and control of haptic devices but also haptic rendering algorithms that can display proper guidance to surgeons. A lot of work is being carried out for employing robots in medical for their potential applications and benefits [9], among them major characteristic is haptics [10]. Haptic rendering could be done using haptic virtual fixtures [11-13], aiming to guide operator towards the task goal. These virtual fixtures can be Forbidden Region Virtual Fixtures (FRVF) or Guidance Virtual Fixtures (GVF). FRVFs prevent tools to enter in undesired or restricted workspace while GVFs help operator to move the tools in the desired path or surfaces in the workspace [14].

In developing haptic guidance, many researchers have focused on rendering the contact forces of instrument tip with the vessel walls to operators through haptic devices. This approach, however, needs a force sensor at the instrument tip. Meiß [15] developed a guidewire with a miniature piezo-resistive integrated at the guidewire tip to distinguish between soft and hard surfaces of plaques. Development of tiny sensor, it's integration with guidewire tip and carrying the signal out of patient's body through microwires is crucial in this scenario. Finally, force vector is rendered to the device appropriately.

The feedback force generated by the guidewire interaction with vessel is important ensuring safe and efficient intervention as these are the clues for the cardiologists. Many tele-operation surgical setups lack this issue, for navigating catheter this becomes very important. Researchers dealt this issue with two techniques, either using a guidewire/catheter with force sensor at the tip or using image based force estimation. One type of haptic feedback is developed in [16]. They developed a robot-assisted catheterization system with the haptic feedback feature allowing physicians to feel the resistance on guidewire proximal end during the remote operation. Estimation of contact forces was done by using a load cell attached in the slave robot while resistive forces were feedback to the master device. Their experimental results showed significant decrease in task completion time for novice and slight increase for experts. Payne [17] also worked on displaying the contact forces in order to avoid the potential damage of blood vessel puncture due to excessive forces via force rendering. A strain gauge was attached at the tip of catheter to measure the contact forces and they were rendered on to the master device. His experimental evaluation showed that force feedback in endovascular catheterization improved the consistency of force exertion and reduced the magnitude of contact forces on vessel walls by more than half. Similarly, different studies focused on development of sensors and/or guidewire/catheter with sensors mounted on tip. A 6DOF force torque sensor is attached at the tool's tip for feeding back force/torque vectors appropriately [18]. Another approach is to use steerable catheters [19-21]. These robotic catheters have numerous DOFs for enhanced dexterity. Another work for navigating catheter inside heart using robot assistance was done in [22]. Feasibility of mentioned above approaches in real scenario is therefore limited due to the difficulties and added expense of sensors mounted at guidewire tip.

Since haptic virtual fixtures have the potential to generate forces/torques by software constraints, they may eliminate the requirement of surgical tools equipped with force/torque sensors. Park et al. [23] was the first reported attempt to introduce virtual fixtures for medical procedures. Later on, researches showed the efficiency of haptic virtual fixtures on different, but not limited to, medical scenarios e.g. cutting, palpation etc. and also cardiac interventions. Park et. al. [24] worked on robotic cardiac catheter navigation system and their work deals only with the forbidden region virtual fixtures for guidance. Their approach can feedback the forces when the tool enters in the forbidden region but cannot provide guidance in advance to avoid tool entering in the forbidden region. In such way using only forbidden region virtual fixtures without guidance virtual fixtures provide limited guidance to operator. Even for training purposes, some researchers have made simulators with haptic devices interfaced with computer for example HERMES [25]. Computer based simulators with haptic feedback can reduce costs of education and training of novice. Simulators have additional benefit that very rare scenarios can be generated again and again for better training. HERMES, for the angioplasty simulation environment, renders the forces/torques to the haptic device [26], [27].

Moon and Choi [28] proposed a tele-operated robotic hardware with PHANTOM as master device while slave robot is 3DOF haptic device, for manipulating both guidewire and catheter. Guo [29] worked solely on the development of haptic device for catheterization. His work proposes an efficient but complex device. Development of haptic interfaces is an active area of research [30], [31]. Very few slave designs have make their way to operation rooms and still research is ongoing. In short, most of the researchers have focused on haptic rendering of contact forces based upon sensors' information mounted at the tip of guidewire.

In this study a haptic guidance system for providing haptic feedback in the robot assisted coronary intervention is proposed. Unlike most of the researches, which require time consuming and expensive preoperative procedures e.g. 3D modeling or 3D imaging, the proposed haptic guidance system can generate haptic guidance feeling through force, torque or vibration display directly from the two available cardiac X-ray images, which are 2D, obtained from C-arm machines. Haptic rendering in the proposed haptic guidance system is based only upon these 2D X-ray images from which combined force/torque fields are generated online after generating VFs only once by indicating on the fixed X-ray image i.e. angiogram. The contribution of this work lies in the methodology of interfacing proposed system with the current C-arm based coronary intervention procedure. This work is novel also in terms of algorithm being used for guidance of operators while they try to position guidewire at target location. Feasibility of the proposed system is validated by comparing operator's performance for different haptic feedback modalities with no-haptic feedback case through experimentation on phantom heart model.

## 1.3 Motivation

Robot assistance can provide a great deal of easiness to the surgeon during Minimally Invasive Surgery (MIS) when surgeon loses direct sight to the organ and eye-hand coordination. In the case of using robots in coronary intervention, many researches were carried out with different methodologies. Currently, haptic feedback methods which researchers have developed for coronary intervention are time consuming and some of them also require expensive pre-operative procedures. For example, after 3D data from MRI or CT, 3D modelling needs to be done as preoperative procedures. Another approach requires special guidewire/catheter with force/position sensor at their tip. Most of the times they are dependent on the position/force sensor at the guidewire tip and read sensors' data or they use image processing to find guidewire tip in image and render contact forces of guidewire tip with the vessels walls to the haptic device. Feasibility of these approaches is limited due to the added expense of sensors mounted on guidewire/catheter tip. Use of robotic steerable catheters have potential to replace conventional methods but it rises development and surgery cost. Or they utilize another option of using computer generated constraints for restricting operator's motion in some region by drawing virtual fixtures. Strictly speaking, they are only using forbidden region virtual fixtures (FRVFs) which restricts operator's motion in some region.

In short, previous researches require special apparatus to be interfaced with machines available in operation room. Moreover, already existing methods have limited capability for providing haptic feedback. My motivation is to propose a methodology which will directly be applicable in operation theater with the C-arm X-ray machines based procedures. Among different X-ray techniques, e.g. CT, MRI, X-ray etc., CT and MRI generate 3D data. Our work focuses on X-ray image based procedure. X-ray images are 2D and this imaging technique is relatively inexpensive and proposed system doesn't require expensive and time consuming preoperative procedures for haptic guidance. A haptic guidance system based upon cardiac X-ray images, with both FRVFs and GVFs should be developed which acquires X-ray images directly from C-arm machines without requiring any expensive preoperative procedures and/or expensive sensorized tools.

### 1.4 Proposed System

Figure 1-4 (a) shows a today's typical operating room for coronary intervention procedures. Figure shows that surgeons are manipulating catheter/guidewire on the patient while looking at two X-ray images (angiogram and real-time fluoroscopic images showing guidewire) that are obtained from C-arm X-ray machine. Normally, during the surgical procedure surgeons are continuously visualizing fluoroscopic images which show guidewire, guide catheter or bone structures having high density. In order to estimate guidewire position and orientation with respect to vasculature, at the start and during the coronary guidewire navigation, surgeons acquires angiogram whenever required, to see the vasculature structure.

This conventional procedure may be replaced by a tele-robotic system. In a tele-robotic system for coronary intervention, a master device manipulates remotely the tools (catheter and guidewire etc.) in a slave robot that is in the operating room near patient. In this case, some kinds of appropriate haptic feedback must be provided to operator (or surgeon) on to the master device because he/she does not have any direct sight and contact with blood vessels of the patient. A typical master-slave robotic system for this job is shown in Figure 1-4 (b).

To give visuo/haptic guidance for operators in tele-robot cardio intervention, 2D X-ray image based haptic virtual fixture algorithm is developed. Since angiograms show coronary arteries, so virtual fixtures are

(a) (b)

Figure 1-4 (a) C-arm X-ray machine for coronary intervention, (b) Master-slave robotic system [7] drawn on the angiogram image over the vascular branches. These virtual fixtures actually show the path to the desired location and are generated by online processing. Surgeons of good knowledge and understanding of angiograms and I believe they can understand and locate infected site across vasculature quite easily. Therefore, in the scenario that more than two surgeons are performing the intervention process, communicating with each other and defining the target location and then drawing the virtual fixtures can be done by one surgeon while another can use master device to carry on guidewire navigation. From the processing of fluoroscopic images in real time, guidewire tip bend is computed. Finally, inner product between virtual fixture and guidewire tip bend is compared to render haptic feedback on to the master device. This haptic feedback consists of force-torque or vibration-torque feedback. Detailed algorithm is described in image processing and haptic rendering part.

### 1.4.1 Basic Premises/Assumptions

Proposed methodology is based upon information available from angiogram and real time fluoroscopic images. Since proposed methodology does not require any force/torque or position sensor on the tools and is dependent on the two available images for haptic feedback, there need some premises which should be followed.

First basic assumption is that X-ray images from pose (position and orientation) adjustment of C-arm should provide optimal 2D view of guidewire and vasculature for the current guidewire position and orientation, and vasculature. This can make the 3D navigation problem along the coronary artery 2D navigation problem. These X-ray images are then fed to a PC program in which some image processing techniques, can generate haptic feedback signals that are necessary to guide the operator through the master haptic device. Second assumption is that the tools (catheters and guidewires) that are used in the coronary intervention are not moving significantly, without manipulation, relative to vasculature even with the heart beating and breathing. This was confirmed by cardiologists. We also observed from many angiograms in the real operations (e.g. as in Figure 1-5) that in most of vascular branches, the angle between two branches does not change its angle significantly and maintain with small angle differences during cardiac/respiratory cycles, angle change measured manually is between 86-92 degrees. For navigating the guidewire, the angular difference between guidewire tip and the vascular angle is important. If there are small angular changes in vascular branches during cardiac and respiratory cycle, it is adequate to use a single static angiogram to cover over real-time algorithm expansion.

However, the cardiac motion and respiratory motion affects the position and shape of coronary blood vessels in angiographic frames. Hence, correlating a static angiogram to the real-time X-ray images is necessary to get correct relative pose between the guidewire and vascular structures. This requires another premise that the cardiac motion and respiratory motions in angiogram are synchronized with real-time fluoroscopic images. Under this assumption, a technique for synchronization of cardiac motion can be employed to compensate motion artifacts. ECG-gating [32] has been used to obtain a stationary imaging for a specific part of cardiac cycle. Yet, the ECG-gating technique is used with breath hold, in real operation, it is hard to ask patients to breath hold. With this regard, a model-based respiratory motion compensation with 3D+t coronary CTA and monoplane 2D+t X-ray angiography has been developed [33]. Authors expect that these studies can be

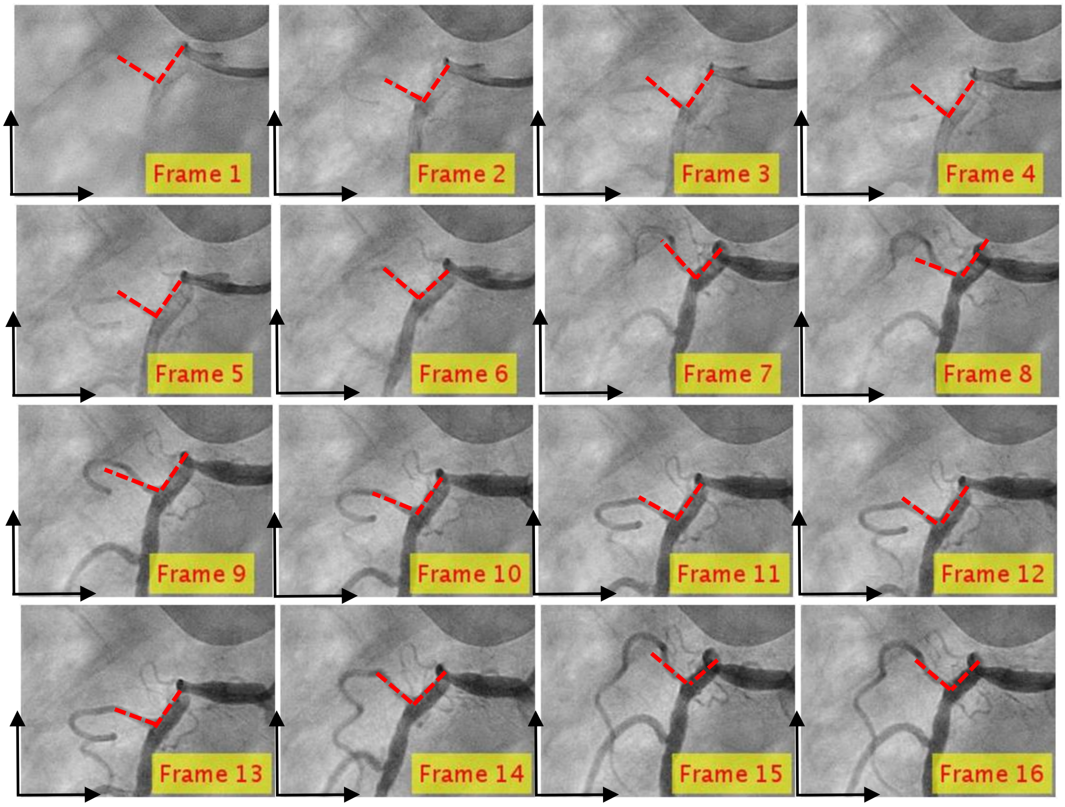



Figure 1-5 X-ray images showing position and angle variation of a vessel branch for six different images captured at 15fps over one cardiac cycle, with respect to the origin shown in black arrow, the angle of branch (shown in red dotted lines) and the location of branch (intersection of red dotted lines is not changing much)

adjustable to the proposed algorithm to synchronize the position and shape discrepancy caused by the cardiac and respiratory motion. Also, by utilizing aforementioned studies, we may solve the relative position between the guidewire and the vascular structures. Hence, it is expected that the position of virtual fixtures and guidewire tip can be synchronized from these aspects.

### 1.4.2 Proposed Haptic Guidance System

Haptic virtual fixtures are used to guide operator for navigating guidewire towards the target location. Virtual fixtures, which are computer generated constraints, are drawn on angiogram image over the blood vessel branches and actually define the pathway towards target location. From the background information of virtual fixtures from angiogram and information of guidewire position and orientation from fluoroscopic images, haptic guidance is rendered to the operator through haptic device. It is obvious that mapping the guidewire orientation in X-ray with respect to blood vessels in angiogram image is easier than mapping guidewire position in fluoroscopic images with respect to vasculature in angiogram. So haptic guidance could be of great importance.

Proposed system entirely relies on the information available from X-ray images which are 2D. In the proposed methodology, a single static angiogram is being used to correlate the guidewire in real-time fluoroscopic images with vasculature. At first, surgeon uses angiogram to draw VFs on them as preoperative procedure. These images after being processed, haptic rendering module of PC program generates feedback forces/torques based upon virtual fixtures. Finally, this feedback is rendered to the master device. Step by step description of proposed methodology is described as follows:

*(Step 1) Virtual Fixtures on Angiogram:*

Proposed methodology involves getting angiogram and drawing VFs on to it online as preoperative procedure. Each VF is drawn at each branch; hence they actually show the path to the target location. Aim is to align the guidewire tip orientation with the VF vector. Every VF on an angiogram is drawn by mouse click and drag, such that the vector from starting point to ending point represents coronary artery’s entrance angle and it’s starting point represents the mid position of the coronary artery branch. The purpose of VF is to guide the surgeon and its fundamental job is to act as Guidance Virtual Fixtures (GVF), but if surgeon is not following guidance then same VF will act as Forbidden Region Virtual Fixture (FRVF) to restrict surgeon’s motions. In this way, a single VF acts as GVF and FRVF under different conditions to better guide the operator.

*(Step 2) Fluoroscopic Image Processing:*

Each fluoroscopic image is being processed at real time by image processing module of PC program to segment guidewire and finally compute (a) guidewire tip position and (b) guidewire tip bend angle in image coordinates. This tip bend angle in 2D image correlates to the tip orientation in 3D. From this information, computer program computes the relative position and orientation of guidewire tip with respect to virtual fixture anatomy and plans the guidance feedback.

*(Step 3) Haptic Rendering:*

With the information available from the image processing and virtual fixtures, it is possible to render haptic feedback on to the master device. While operator is navigating guidewire towards target location using master device. Each frame of image is being processed by step 2 and haptic guidance composed of guidance torque and guidance force, is rendered. When the guidewire tip is at the close proximity of vessel branch, guidance torque for adjusting tip orientation and guidance force for adjusting tip position is rendered to navigate to target location.

Updating the conventional guidewire navigation procedure in the operation room involves surgeons manipulating guidewire using master device instead of their hands while slave robot follows master device's motions. Additional equipment required is a PC to process X-ray images and to render haptic feedback. To validate our results in the laboratory we used a web cam as image acquisition device and phantom heart model as vasculature test bed.

## 1.5 Contributions

Unlike most of the researches which require time consuming and expensive preoperative procedures e.g. 3D modeling or 3D imaging [13], the proposed haptic guidance system can generate haptic guidance feeling through force, torque or vibration display directly from the two available cardiac X-ray images, which are 2D, obtained from C-arm machines. Haptic rendering in the proposed haptic guidance system is based only upon these 2D X-ray images from which combined force/torque fields are generated online after drawing VFs only once on the fixed X-ray image i.e. angiogram image. The contribution of this work lies in the methodology of interfacing proposed system with the conventional coronary intervention procedure. This work is novel also in terms of algorithm being used for guidance of operators while they try to position guidewire at target location. Feasibility of the proposed system is validated by comparing operator's performance for different haptic feedback modalities with no-haptic feedback case through experimentation on phantom blood vessels.

### 1.6 Thesis organization

Rest of the thesis is organized as: Chapter 2 explains X-ray image processing and the methodology that image processing results are being used to create haptic rendering. Chapter 3 describes the hardware and software components of experimental setup. Experimental protocol and results are discussed in Chapter 4. Finally, conclusions are drawn along with future works in Chapter 5.

# 2. Haptic Guidance based on Cardiac X-ray Images

In this chapter, the idea of haptic virtual fixture for cardiac intervention based upon cardiac X-ray images is introduced. Guidewire tip position and orientation is computer using image processing module of PC program which is in turn used for haptic feedback generation. As stated earlier, in the preoperative procedure virtual fixtures are generated on the angiogram. Procedure of drawing virtual fixtures and their associated attributes are explained in 2.2. Haptic guidance is provided on the master device based upon the information available from the virtual fixtures anatomy and guidewire current position and orientation from image processing module running at 15Hz.

## 2.1 Image processing

Goal of image processing is to compute the guidewire tip position and orientation in the image. A tangent at the tip is generated which estimates the tip bend in 2D image and this tangent correlates to tip orientation in 3D. Proposed methodology for haptic feedback relies entirely on the information available from the cardiac X-ray images acquired from C-arm X-ray machines. Without doing cardiac X-ray image processing, it is not possible to know the guidewire tip position and orientation with respect to vasculature and hence definitely would not possible to guide the user through haptic devices. Following steps are used to accomplish the job of image processing for a phantom heart model environment.

### 2.1.1 Guidewire segmentation

Multiscale vesselness filtering [34] was used for performing the guidewire segmentation in the image. X-ray images, without contrast enhancement medium, contains only the guidewire, guide catheter and dense bone structures with background noise. This filter searches for the vessel like structures and since guidewire is radiopaque material which makes guidewire easily contrasted from the background image, so the guidewire structures are well detected as well. A comparison is made between different vessel enhancement filters which shows that Frangi filter has higher sensitivity for detecting vessel like structure [35].

According to Frangi's work [17], a common approach to analyze the local behavior of an image, $I(x)$, is to consider its Taylor expansion in the neighborhood of a point $x_o$,

$$I(x_o + \delta x_o, \sigma) \approx I(x_o, \sigma) + \delta x_o^T \nabla_{o,\sigma} + \delta x_o^T H_{o,\sigma} \delta x_o \quad (2\text{-}1)$$

This expansion approximates the structure of the image up to second order. $\nabla_{o,\sigma}$ denotes gradient and $H_{o,\sigma}$ denotes Hessian matrix of image computed in $x_o$ at scale $\sigma$.

Performing the analysis of Hessian matrix as:

$$H_{o,\sigma} \hat{u}_{\sigma,k} = \lambda_{\sigma,k} \hat{u}_{\sigma,k} \quad (2\text{-}2)$$

Here $\lambda_{\sigma,k}$ is the eigenvalue corresponding to the k-*th* normalized eigenvector $\hat{u}_{\sigma,k}$, computed at scale $\sigma$, of the Hessian $H_{o,\sigma}$. Using the three eigenvalues ($|\lambda_1| \leq |\lambda_2| \leq |\lambda_3|$) with the k-th smallest magnitude, the combination of following ratios is used to define a vessel likeliness function:

$$R_B = \frac{|\lambda_2|}{|\lambda_3|} \quad (2\text{-}3)$$

$$S = \|H\|_F = \sqrt{\sum_{j \leq D} \lambda_j^2} \quad (2\text{-}4)$$

$R_B$ is the measure of deviation from blob like structure. In order to suppress the background noise, Frobenius matrix norm is used as in (2-4), this measure will be low in the background because of low contrast hence having small eigenvalues. For 2D X-ray image, vessel likeliness function is defined as:

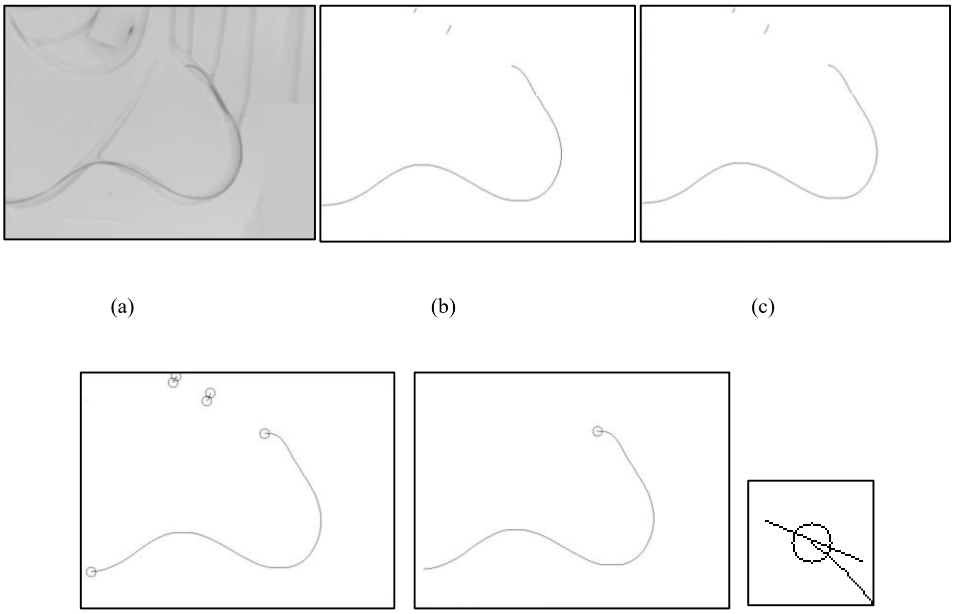
$$v_o(s) = \begin{cases} 0 & if \lambda_2 > 0, \\ exp\left(\frac{-R_B^2}{2B^2}\right)\left(1 - exp\left(\frac{-s^2}{2c^2}\right)\right) & \end{cases} \quad (2\text{-}5)$$

In (2-5), $B$ and $c$ are tuning parameters for response of the function. For a phantom model input image as in Figure 2-1 (a), a typical resultant image by applying multiscale vessel enhancement filter looks like as in Figure 2-1 (b) which is a grey scaled image.

### 2.1.2 Guidewire tip detection

Once the guidewire segmentation is performed, guidewire is detected but there is also background noise in the filtered image. As first step to remove noise elements, grey-scaled image was converted to binary with fixed thresholding. Taking into account guidewire as a single pixel width of curve for the rest of the image processing, Gonzalez thinning algorithm for acquiring skeleton of each binary region was applied Figure 2-1 (c). Now it is easy to manipulate the skeleton of guidewire for tip detection and also to remove the noise elements.

Furthermore, another problem arises with the fact that most of the times guidewire segmentation is not continuous. To deal with this problem, firstly, end of curve detection algorithm was run throughout the image. This algorithm states that only that pixel is said to be the end of curve pixel if and only if it has exactly one pixel in its neighborhood. Running this algorithm through the whole image pointed out all of the end of curve pixels including the noise pixels Figure 2-1 (d). Then we connected two adjacent end points if the distance between



(a) (b) (c)

(d) (e) (f)

Figure 2-1 Image processing results, (a) Guidewire inside phantom model, (b) Frangi filter, (c) Binarization and Gonzalez thinning, (d) End of curve detector, (e) Noise removal with guidewire tip detection, (f) Guidewire tip bend tangent them is less than or equal to threshold. Those points which are far apart are not connected, in this way any discontinuities in segmented guidewire were removed. Next, we applied the algorithm to remove the binary regions which have area less than some threshold. Finally, as now the image is available only the guidewire segmentation. Once again end of curve detection algorithm was run through the whole image pointing out starting and ending pixels of guidewire in the image and guidewire tip is chosen and a circle is drawn Figure 2-1 (e).

### 2.1.3 Guidewire tip bending angle

Guidewire tip bend angle in the 2D image is actually used to estimate its orientation in 3D plane. Starting with cropping the guidewire segmented image of the dimensions 63x63 such that cropped image contains the guidewire bend the x-y map of guidewire pixels was recorded for each frame. In computers, origin of coordinate system is at the top left corners, to make the origin at the bottom left simply inversion of vertical axis values (rows) was performed.

Next, curve fitting algorithm was applied utilizing open source, GSL Scientific Library, to compute the curve fitting for second order polynomial on to those pixel locations for which guidewire is detected in cropped window. Since higher order are more sensitive to noise and a little change in the guidewire segmented image could result in curve of different coefficients, so to avoid that we found that curve fitting of second order was effective. Once the curve for tip bend is computed, it is straight forward to compute the tangent at tip location using polynomial coefficients $a$, $b$ and $c$ with x-axis values $x$ and y-axis values $y$.

Second order polynomial equation:
$$y = ax^2 + bx + c \tag{2.1}$$

$$\dot{y} = 2ax + b \tag{2.2}$$

This derivate is actually the slope of tangent.

So using the line equation, we can find the equation of tangent.

$$y = mx + b \quad where \quad m = \dot{y} \tag{2.3}$$

## 2.2 Haptic rendering

Aim to incorporate haptic feedback is to design a more effective strategy for guidewire navigation towards target site in the heart. Haptic rendering algorithm is intended to align the guidewire tip bend according to the haptic virtual fixture vector when the guidewire tip is at close proximity to the coronary vessel branch. To enter in the desired branch, a virtual fixture is already drawn there in preoperative procedure and so haptic guidance is being provided accordingly.

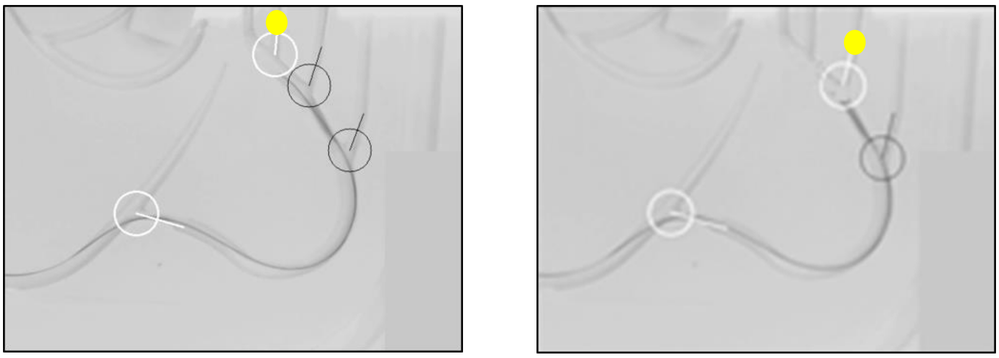
While navigating the guidewire through the coronary arteries, surgeons' use two degrees of freedom (DOF) of master device, named translation and twist, to maneuver guidewire in 3D inside heart. Haptic rendering is provided to both of the DOFs of master robot. Estimating relative position of guidewire tip from the blood vessel branch entrance is important in a way that if the guidewire tip orientation is adjusted in advance i.e. while guidewire tip is far from the blood vessel branch then it may or may not be possible to enter in that specific coronary vessel branch at first try. Better strategy is to adjust the tip orientation when guidewire tip is at close proximity to that branch entrance. Once tip orientation is properly adjusted then it is most likely that guidewire would successfully enter in the desired branch at very first try. Hence providing a feedback on the translational DOF, when guidewire tip is at close proximity to the branch prior to feeding back torque feedback is crucial in order to alert operator to stop further push/pull before setting guidewire orientation. Next, torque feedback is rendered to the twisting DOF, which is helpful for aligning the guidewire tip orientation to the desired branch.

Generally, haptic virtual fixtures are generated using preoperatively on angiogram. Yet, for the case of coronary artery intervention, these virtual fixtures are drawn on the angiograms which are acquired at the start or during the procedure. The proposed virtual fixture algorithm consists of combined Forbidden Region Virtual Fixture (FRVF) and Guidance Virtual Fixture (GVF) together, and a single virtual fixture acts as FRVF and GVF under different scenarios. The methods and details are described as below.

Each virtual fixture is generated by mouse click and drag followed keyboard key press 'A' for attractive (in white color) or 'R' for repulsive (in black color) VF. VF is drawn such that the starting point of each virtual fixture is at the starting of the blood vessel branch, at approx. half of the width of blood vessel, while ending point is inside the same branch, at approx. half of the width of blood vessel. Hence this vector represents coronary artery's entrance angle and the starting point of this vector represents the mid position of the blood vessel branch, in this way it is judged whether or not the guidewire tip is crossing or has crossed the blood vessel branch entrance. For each virtual fixture a circle is drawn with the center at the starting point of virtual fixture vector. The diameter of this circle is 60 pixels (approx. 8.4mm) and maximum distance of guidewire tip from the center of this circle is 30 pixels (approx. 4.2 mm). This distance will be referred as distance of influence and this circle will be referred as field circle. Idea is to set guidewire orientation according to the VF vector when tip is inside field circle.

Repulsive virtual fixtures make sure that guidewire does not enter in that vessel branch while attractive virtual fixture generates force/torques to allow operator to enter guidewire in the corresponding vessel branch. For an attractive virtual fixture, force feedback will be directed so as to attract guidewire tip towards the center of field circle and tip bend will be maximum aligned with virtual fixture vector. For a repulsive virtual fixture, force feedback behavior is the same but tip bend is adjusted such that it is maximum in the opposite direction of virtual fixture vector in order to avoid entering in undesired branch.

Marking of the attractive or repulsive virtual fixtures depends upon the structure of coronary arteries and target location. Figure 2-2 shows two different schemes of marking VFs for two different target locations, target locations shown in yellow mark. Virtual fixtures schematic makes sure that guidewire reaches target location without entering undesired branches.



(a) (b)

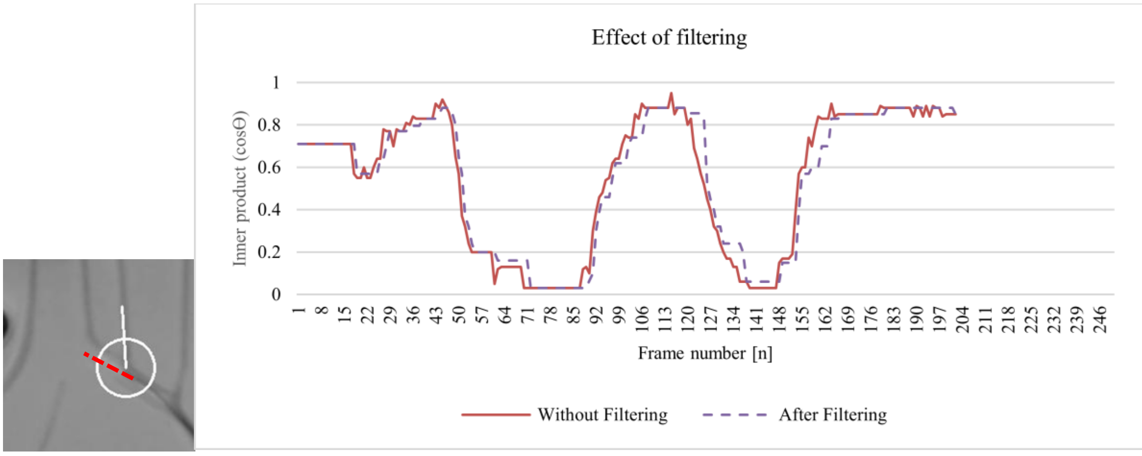
Figure 2-2 Two different configurations of virtual fixtures for two different target locations

### 2.2.1 Haptic rendering algorithm

Due to the image noise and insufficient quality of image segmentation results, jitter usually appears in the tangent vector. This jitter can affect the quality of torque feedback, because magnitude of torque is proportional to the inner product between the guidewire tip vector and virtual fixture vector. In the interest to reduce the jitters, low pass filtering is first applied then the following algorithm is used to smooth the inner product, where *[n]* denotes current inner product sample for the current image frame:

- if previous two samples *[n-2]* and *[n-1],* show increasing behavior in inner product and current sample *[n]* shows decreasing behavior ignore it as noise otherwise accept it as data
- if previous two samples *[n-2]* and *[n-1],* show decreasing behavior in inner product and current sample *[n]* shows increasing behavior ignore it as noise otherwise accept it as data

For an attractive virtual fixture and tip tangent (shown in dotted red line) as in Figure 2-3 (a). The result of filtering is depicted from the Figure 2-3 (b), where *Θ* is the angle between the guidewire tip tangent and virtual fixture vector. Guidewire was continuously rotated in one direction and inner product values were recorded, and after filtering behavior of inner product was either increasing or decreasing monotonically.

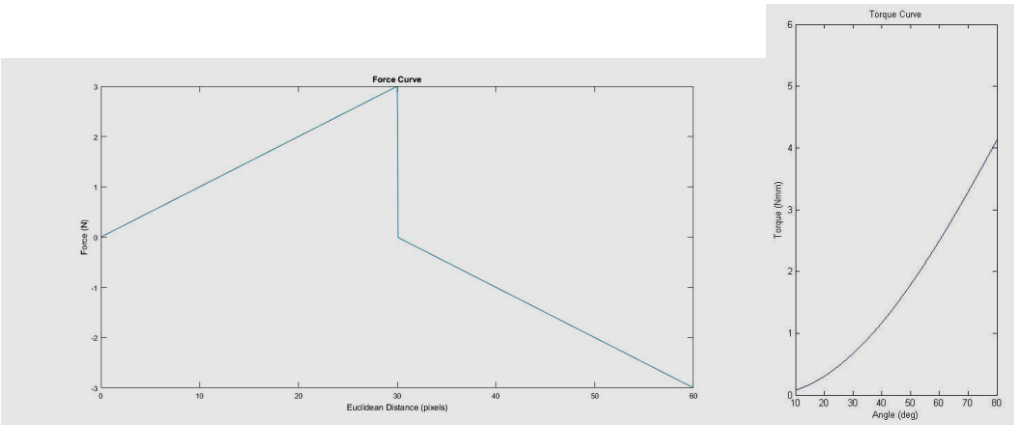



(a) (b)

Figure 2-3 Inner product filtering result

Proposed haptic rendering aims to minimize the inner product between the guidewire tip bend vector and the vector of blood vessel entrance (as it is drawn using virtual fixture) when the guidewire tip is near the vessel branch entrance. We have provided haptic rendering on both translational and rotational DOF. When the guidewire tip is outside the field circle there is no haptic feedback and user can move freely alike normal operations, where surgeons are continuously rotating and translating the guidewire while navigating towards desired site. But when the guidewire tip is inside the field circle, a feedback is provided on the translational DOF, which alerts the user that guidewire tip is near the blood vessel entrance and further push or pull of guidewire should be stopped until the guidewire tip orientation is properly adjusted. Next, the user is required to rotate the guidewire in either direction, clockwise or counter clockwise) aiming to align tip orientation with the branch angle. Meanwhile, a guidance torque is provided until the guidewire tip bend orientation is either maximum aligned with the virtual fixture (in the case of attractive virtual fixture) or maximum out of alignment (in the case of repulsive virtual fixture). When orientation is adjusted then user is supposed to start pushing/pulling of guidewire towards target location.

Haptic feedback on translational part has two modalities a) force feedback b) vibration feedback. In the case of force feedback, magnitude of force is proportional to the distance of guidewire tip from the center of the field circle. An attractive force, which attracts the guidewire tip towards the center of field circle, is generated at the moment when guidewire enters the field circle. If the guidewire tip has crossed the center of field circle, a repulsive force is generated guiding the user to be at the center of field circle, force feedback curve is shown in




(a) (b)

Figure 2-4 (a) Force feedback curve, (b) Torque feedback curve

Figure 2-4 (a).

In the case of vibration feedback modality, vibration feedback is provided to the user when the guidewire tip is at the distance of 10 pixels (1.4mm) from the center of field circle. Vibration feedback is modulated on frequency and amplitude. When the guidewire tip is near the field circle, vibration of certain amplitude and frequency (2mm and 30Hz, respectively) is applied and if the user has passed through the field circle then vibration of another amplitude and frequency (7mm and 50Hz, respectively), both higher than previous is provided alarming the user about the situation i.e. tip is at close proximity to the blood vessel entrance.

Once the position of guidewire tip is adjusted, next user is supposed to twist the guidewire in either direction then if the initial direction of rotation is correct, an assistive torque is generated otherwise torque in opposite direction is generated to adjust guidewire tip orientation. Torques, magnitude shown in Figure 2-4 (b), are computed based upon the inner product difference between the virtual fixture and tip tangent vector. The goal is to maximize the inner product for the attractive virtual fixture and to minimize the inner product for the repulsive virtual fixture. This graph explains the step by step procedure involved in adjusting the torque.

$$F = k \ d \tag{2.4}$$

$$F = A \ \ \sin 2\pi f t \tag{2.5}$$

$$T = G \tag{2.6}$$

Above equations are used for creating the feedback force and torque. Equation (2.4) is used for force feedback, $k$ is the gain and $d$ shows the distance of guidewire tip from the field circle center. $A$ is the magnitude while $f$ and $t$ are frequency and time respectively used in (2.5) for creating the vibration feedback. Parabolic gain was used to feedback torques to operator as in (2.6), $G$ and $\Theta$ are gain and inner product difference respectively.

Figure 2-5 (a) explains the overall haptic feedback algorithm based upon the inner product between guidewire tip bend and VF vector for an attractive VF. Goal is to enter inside this branch and target location is marked by red dot while dotted line in red color shows guidewire tip bend. Here at the start, guidewire tip is outside of any circle i.e. more than 15 pixels away from entrance Figure 2-5 (b). If guidewire tip is not inside the circle then user and freely rotate and twist the guidewire.

*Step 1* tells that operator has entered the field circle and is alerted by either force feedback or vibration feedback rendered on translational DOF (Figure 2-5 (c)). Operator should stop further push/pull of guide until the guidewire tip bend is adjusted.

*Step 2* Operator is supposed to twist the guidewire in order to adjust the guidewire tip orientation. The guidance torque is applied until the inner product is increasing. At the moment inner product starts decreasing, twisting actuator's position is marked and its position control becomes active restricting operator to rotate any further, so as to sure that guidewire remains in the optimal position. Figure 2-5 (d) shows that guidewire tip bend is maximum aligned with the virtual fixture vector.

*Step 3* Next, operator is supposed to push the guidewire forward to enter in the targeted vessel, Figure 2-5 (e).

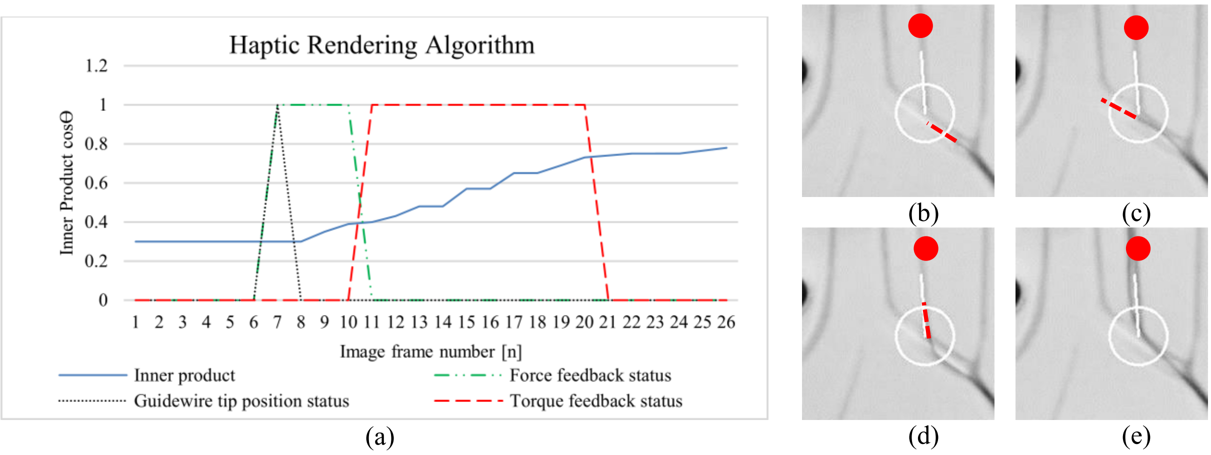



Figure 2-5 Haptic rendering algorithm step by step

# 3. Experimental Setup

This chapter briefly introduces the hardware of system; master and slave robots' mechanism and PC software. The computer, because of having very high computing power, is used for X-ray image processing and haptics rendering. However, all the control is applied in the DSP, which is embedded processor, because of accurate clock and precise delays. In the last of this chapter, PC program architecture for different modules is also explained in detail.

Figure 3-1 shows architecture of experimental setup comprising of different hardware and software modules connected with PC program. A webcam is used as image acquisition device which is attached right above the phantom heart model. These images are processed by the image processing module of the PC program to generate haptic feedback by the haptic module of PC program and it is rendered on to the master device. Master device not only reads the operator's actions but also acts as haptic display. The slave device is in position control mode and follows master device's motions.

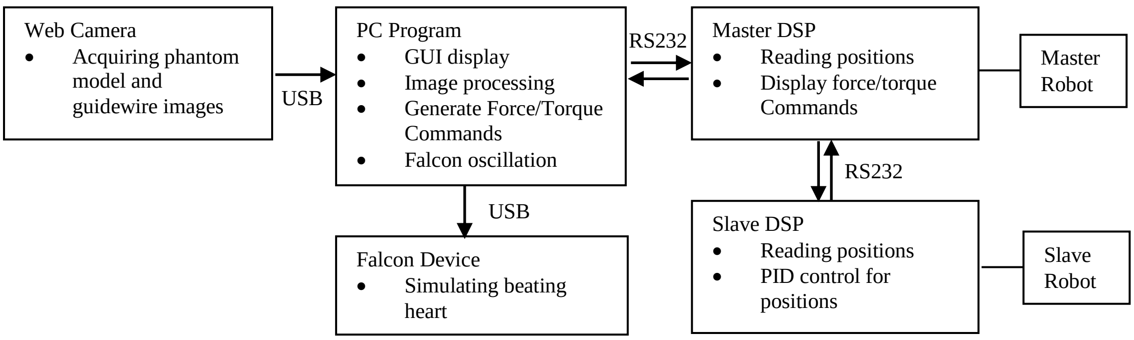



Figure 3-1 Block diagram of system

## 3.1 Hardware components

Hardware components include an image acquisition device, master and slave robot and their embedded circuitry and falcon device. Embedded circuitry consists of TI's DSP (TMS320F27377S) as microcontroller running at 200MHz clock frequency. Two identical circuits, one for master device control and one for slave device control are interfaced through a serial communication link. Master and slave devices have two DC motors each connected with EQEP (Enhanced Quadrate Encoder Pulse: Module dedicated for quadrate encoders) of DSP for reading position information. Additionally, master robot circuitry is connected with PC program via another serial communication link. A phantom blood vessel model is supported by falcon haptic device used as test bed for experimentation. Falcon is programmed to oscillate the phantom model to simulate heart beating.

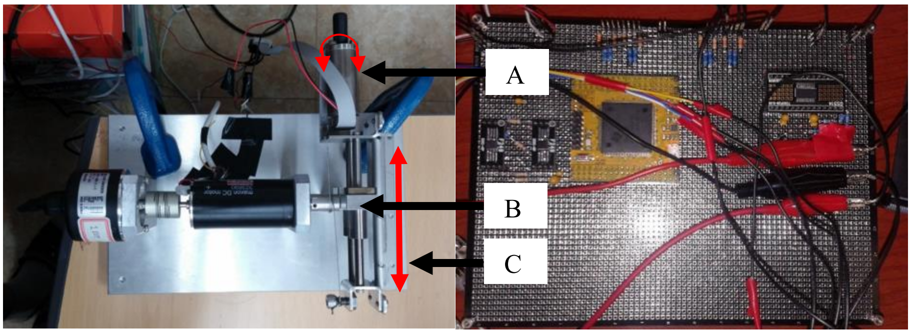
A phantom blood vessel model made up of plastic material is used for experimental purposes as shown in Figure 3-3. Two falcon devices are used to support the weight of phantom model and to simulate heart beating Figure 3-2. Master and slave devices' mechanisms and are explained next.

Figure 3-2 Falcon assembly for simulating beating heart

Figure 3-3 Phantom blood vessel model

### 3.1.1 Master device

We developed master-slave robotic system to accomplish the job of guidewire manipulation/navigation inside patient's heart. Master device consists of a robot with 2DOF as in Figure 3-4 (a), namely translation and twisting, and its control circuitry Figure 3-4 (b). We targeted the development of robotic system such that it allows user to perform conventional hand motions for guidewire navigation as in Figure 1-3 (b), increasing adaptability of our system for them.




(a) (b)

Figure 3-4 (a) Master device, (b) Master DSP board

(A) Twisting DOF, (B) Wire driven mechanism for translational link movement, (C) Translation DOF

Master device serves the job of reading motor positions as well as haptic display: displaying synthetic forces and torques in response to various measurements Figure 3-4 (a). Different researchers have worked on developing master/slave devices but either they are not cost effective or expensive in terms of manufacturing cost. Master device that we developed is simpler in mechanism yet serves the same purpose with simpler mechanism design. The translational link has stroke length of 54.6mm. This link is at the middle position of total stroke length i.e. at 27.3mm, this means that operator can move the link, and hence guidewire, in either direction: either forward or backward to the maximum of half of stroke length. Master device is also equipped with a touch sensor working as clutch. When the operator is holding the master device, every movement of master device is mimicked by the slave device. When the operator is not grasping the master device, the translational link comes back to its normal position i.e. middle of stroke length, while during this time slave device doesn’t make any movements hence clutch operation is accomplished. The translational part is actuated by a DC motor through a wire wrapped around a screw thread like structure as shown in Figure 3-4 (B). This can be considered as helical spring and translational distance can be computed as:

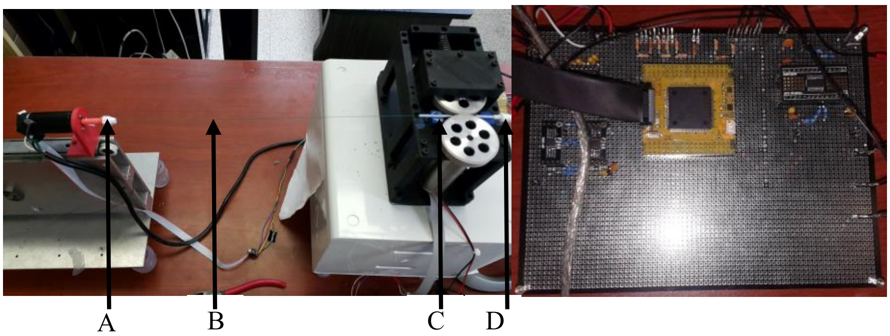
$$arc\ \ length = translation\ \ displacement = \sqrt{r^2 + \left(\frac{\rho}{2\pi}\right)^2}\,\theta \tag{3.1}$$

where $r$: a cylinder radius [mm], $p$: pitch [mm], and $\theta$: rotation angle of the translation motor [rad].

The position and velocity resolution of master robot is 0.00128647 mm/count and 5.1458764 mm/s, respectively, at 4KHz control rate. The twisting DOF allows the operator to twist the guidewire in CW/CCW direction while trying to adjust its orientation according to the desired blood vessel entrance.

### 3.1.2 Slave device

Slave device consists of a mechanical assembly and its control circuitry Figure 3-5. Slave device is similar to master device in terms of functionality i.e. maneuver the guidewire in 3D with 2DOF actuation, namely translation and rotation. These 2DOF are enough to maneuver the guidewire with tip bend. Slave device is in position control mode. Master device sends its position information to slave device at 1KHz. Two PID control loops running at 1KHz in slave DSP control the translational and rotational positions, individually. The purpose of having this kind of schematic is to making cardiologist free from the requirement to be present in the same compartment to that of patient ensuring his health as X-rays are injurious to health.




(a) (b)

Figure 3-5 (a) Slave robot, (b) Slave DSP circuitry

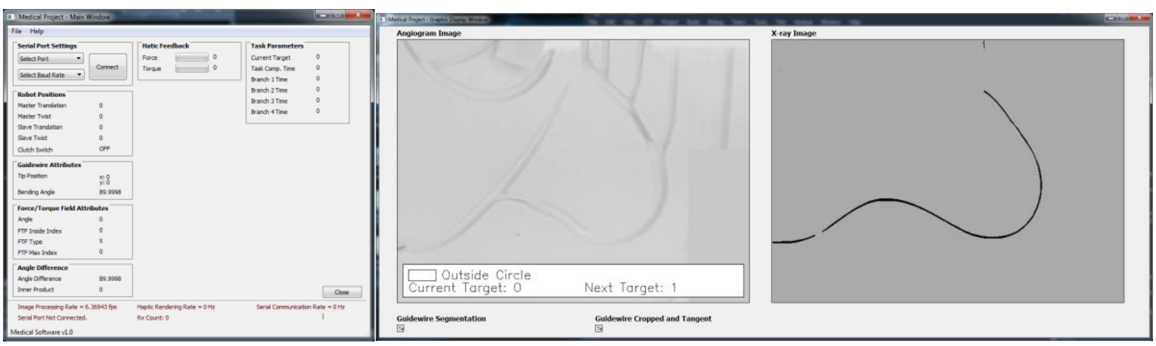
(A) Rotational DOF and guidewire held in chuck, (B) Guidewire, (C) Translational DOF, (D) Catheter

Mechanical mechanism consists of a rotational link and a translational link. With the rotational assembly, guidewire is gripped in the chuck which is attached with the rotational motor's shaft as in Figure 3-5 (A). Rotation of this motor rotates the guidewire hence responsible for rotational DOF. After the rotational assembly, guidewire being gripped between two rollers, which are rotated by the another motor, is translated forward/backward thus accomplishing translational DOF Figure 3-5 (C). When these rollers rotate, guidewire is translated in direction of tangential velocity of rollers. This guidewire slides inside of a catheter, while the catheter in Figure 3-5 (D), is being held at the end of slave device. Appendix A shows the circuit schematic of master and slave devices.

## 3.2 Software modules

Software modules consist of master DSP program, slave DSP program and PC program. Master DSP program reads the motors' position through quadrature encoders, receives slave motors' position data from slave DSP and sends all this information to PC program through serial port. It is also responsible for receiving force/torque data from PC program and renders that force/torque on to the device actuators. Slave DSP program reads the motors' position through quadrature encoders, receives master motors' position information through serial port and runs two PID controls, one for each motor position control in order to follow master robot movements.

PC program, which is the heart of whole system, consists of four major threads with two additional threads for GUI manipulation. PC program is C++ based with Qt library for GUI development, two different windows are used; Figure 3-6 (a) shows main window: for display numeric data about system e.g. robots' positions, guidewire tip information etc. Figure 3-6 (b) shows another window which is child window displaying live X-ray and static angiogram.




(a) (b)

Figure 3-6 (a) Main window, (b) Child window

Both of the GUI windows have update rate of 15Hz. OpenCV library is used for image processing and processed images are shown on child window. Main window can also take inputs from user for connecting with the appropriate serial port and appropriate baud rate. There is another separate image window, named Angiogram VF Window generated by OpenCV, to draw virtual fixtures on to the angiogram.

All of the threads are mutex protected ensuring safety and reliability of code to work without crashing. Appendix B shows the flow of code. Four major threads are:

a) Serial communication thread: Running at 1KHz, communicates master DSP in full duplex mode.

b) Image processing thread: Running at 15Hz, processes X-ray images.

c) Haptic rendering thread: Running at 1KHz, responsible for force/torque calculations.

d) Falcon control thread: With control frequency of 1KHz, produces oscillatory motion of both falcons to simulate heart beating.

Physically, a webcam is attached right above the phantom model for image acquisition. Catheter is attached with the slave robot and then it is placed in one of the entrances of phantom vessel structure. Before attaching the guidewire with the slave robot, its tip is initially bent according to the blood vessel structure and target location. This guidewire is passed through this catheter and then navigated to the target location through the master robot while slave robot is performing similar actions to that of surgeon.

# 4. Experiment, Results and Discussions

Only the visual information is shown on to the PC program while operator manipulates guidewire watching images on the monitor screen. During the experiment only the child window Figure 4-1 (a), is shown to the operator. This child window contains two images; one image shows a single static angiogram with vasculature clearly visible while other shows only the guidewire.

Before the experiment, guidewire initial tip bend angle is appropriately made according to the vasculature. At the start of experiment user takes the angiogram image which clearly shows the blood vessel structure Figure 4-1 (b). Virtual fixtures are drawn on to this separate image to avoid occlusion due to virtual fixtures. Adjacent to angiogram in the child window, live stream of guidewire is shown. On the test bed of phantom heart model, we tested our algorithm in the laboratory such that after generating virtual fixtures, subject has to correlate single static angiogram with the live guidewire images while navigating towards target location.


(a) (b)

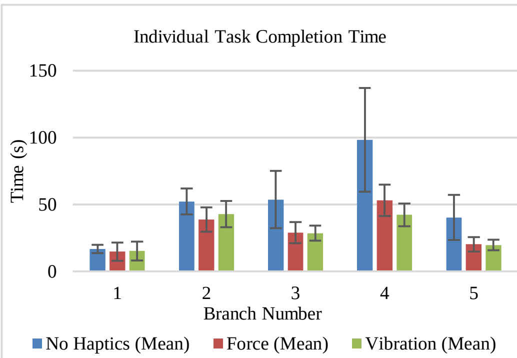
Figure 4-1 (a) Child window with static angiogram and live x-ray images, (b) Virtual fixtures on angiogram

For the experiment, ten subjects (8 males, 2 females, ages 22 – 27) were participated. Most of the subject (i.e. 7 subject) were not familiar with kinesthetic haptic feedback and with PCI manipulation. Therefore, in the training session they were given 30 minutes to have hands on experience of the given system by performing the task of positioning guidewire at the target location. Each session contains three trials, without haptic feedback mode, force-torque feedback mode and vibration-torque feedback mode. Each subject was required to perform the task of reaching the target locations one by one. In addition, we blocked undesired branches with virtual fixtures (in black lines as shown in figure) which become active only when current branch is not of interest. We measured task completion time i.e. time from target 0 to target 5 and individual task times as well.

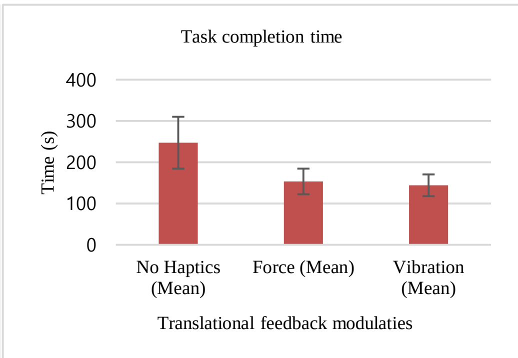
### 4.1 Experimental results

Figure 4-2 (a) shows the time for positioning guidewire tip at each target location. From the measured times, it is evident that branch 4 is the most difficult branch while branch 1 is easiest and branch 2, 4 and 5 are of mediocre difficulty levels. Without haptics feedback, operators took more time to complete their task and show more variability as compared to haptics feedback.

Figure 4-2 (b) clearly shows significant decrease in task completion time when haptics feedback (force-torque or vibration-torque) is provided to the user. However, ANOVA shows that there isn't significant difference between the force-torque feedback and vibration-torque feedback. In case of no feedback average task completion time in seconds is 246.90±69.34. This time is reduced by 37.12% to 155.23±25.96s for force-




(a)




(b)

Figure 4-2 Experimental results

torque feedback while it is 148.66±18.01s in the case of vibration-torque feedback which is quantitatively slightly better than force-torque feedback. However, in terms of qualitatively measurements, 8 out of 10 subjects voted for vibration-torque feedback, 1/10 voted for force-torque feedback. While another 1/10 voted that no feedback is better because he was having good skills for guidewire manipulation and feedbacks that he doesn't have to rely on haptic feedback.

# 5. Conclusions and Future Works

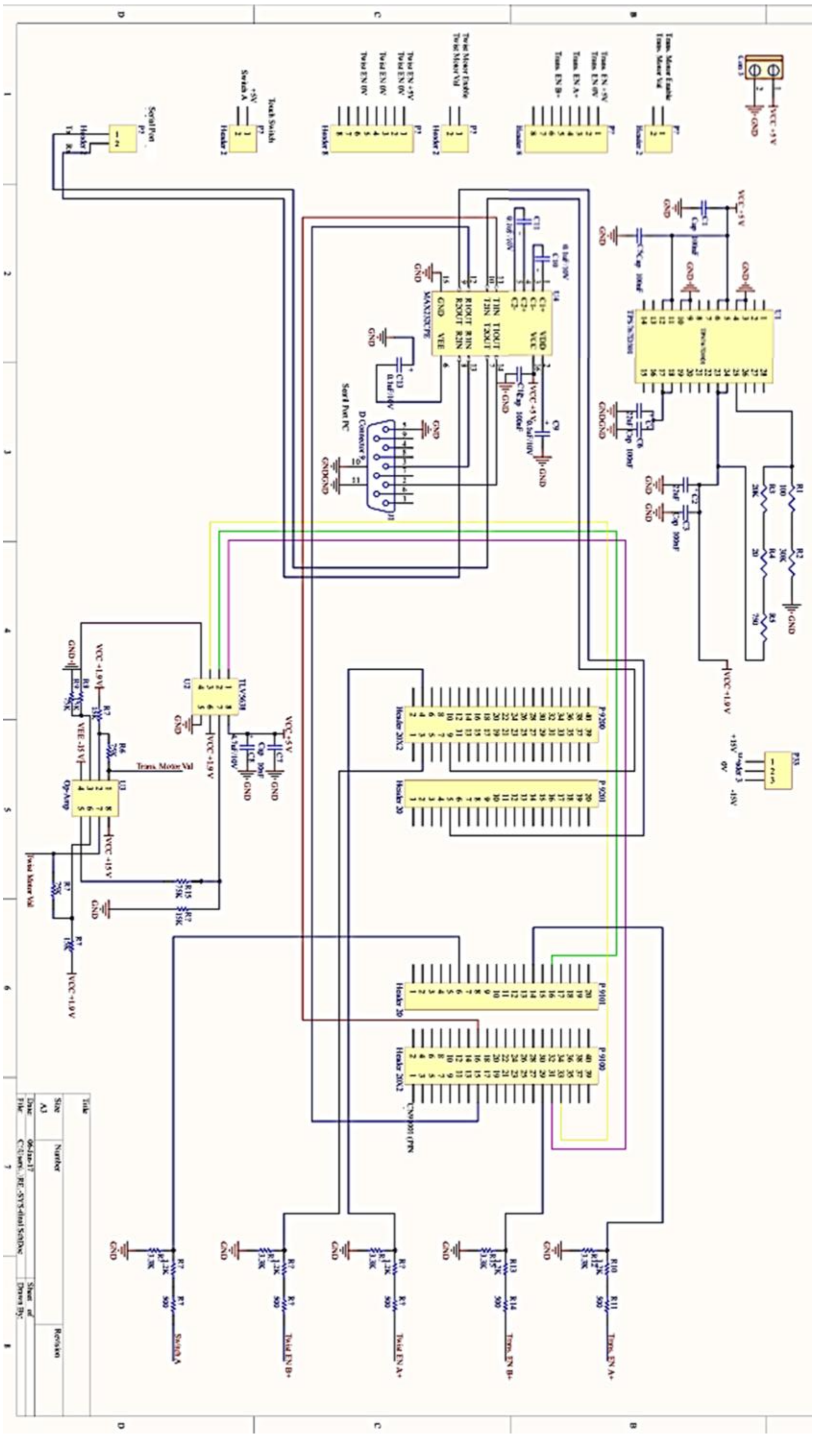
In this thesis, we presented a system compatible to C-arm X-ray machines for guidewire navigation having the feature of haptic guidance. Appropriate haptic guidance is being provided through X-ray images which are 2D. Unlike other researches which require expensive and time consuming preoperative procedures, our methodology requires only generating of virtual fixtures as preoperative step.

Through the experiments we showed that proposed haptic guidance system is helpful to improve the performance of subjects in terms of reducing task completion time for coronary intervention. Haptic rendering is most efficient for most difficult branch while for easiest branch it is not very helpful and for branches of mediocre difficulty levels haptics is again better than no haptics case. Results show that force feedback for translational DOF could be replaced by simply vibration feedback, as vibration actuator is comparatively inexpensive so device cost is reduced and most importantly, it is possible to generate haptic feedback relying on 2D X-ray images. We showed that 2D images are good enough to assist operator to navigate the guidewire in 3D inside the heart. Using our methodology, we expect that frequency of acquiring angiograms will be reduced resulting in low dose of contrast medium which is actually toxic. Secondly haptic guidance helped users to know about the relative position and orientation of guidewire tip with respect to blood vessel structure and so haptics assisted users to perform task faster.

The following research will be performed hereafter; clinical evaluation of proposed system on to the animals is needed for deploying the system in operation room. automatic drawing of virtual fixtures on the angiogram images upon vessel segmentation. This requires automatic drawing of virtual fixtures on the angiogram image, correlating the angiograms with the current fluoroscopic image using ECG gating and controlling the position of orientation of C-arm of X-ray machine.

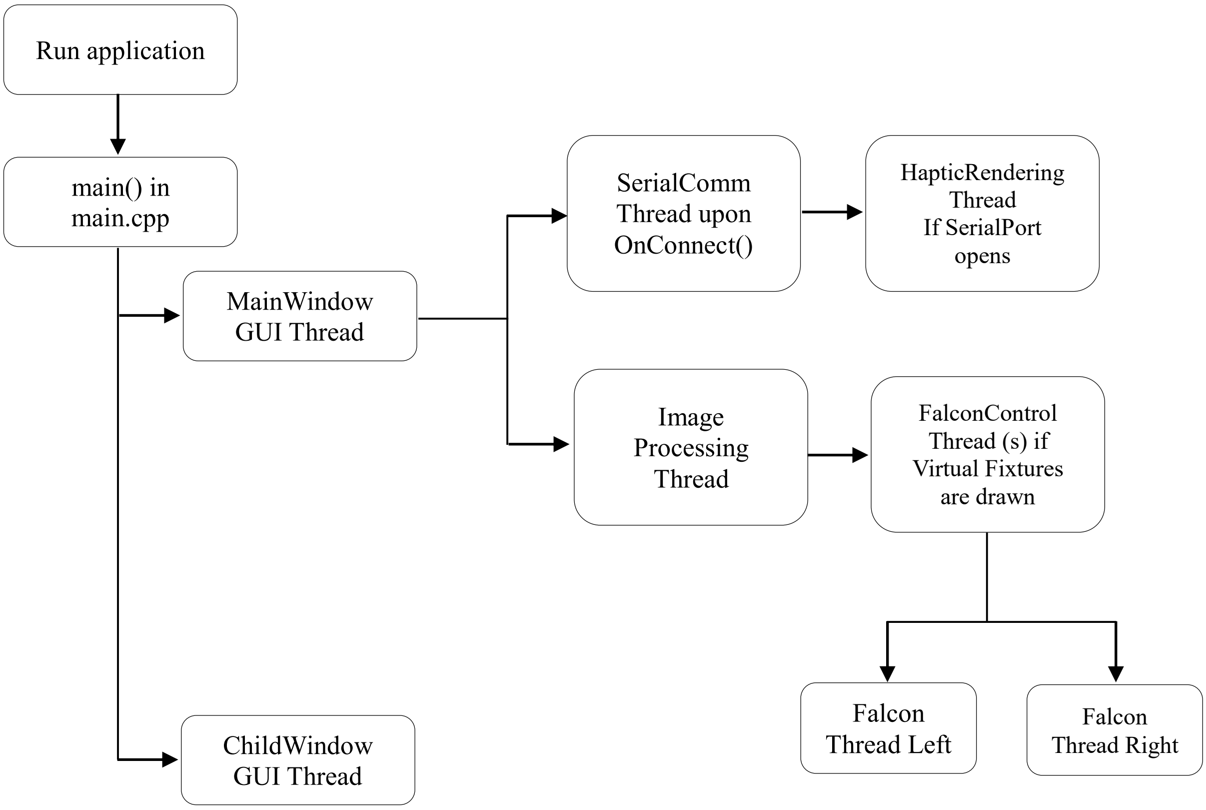
# Appendix A: Circuit Schematic

This is the schematic of master device control circuitry, slave device's is same except that there is no touch switch and only one serial port is being used.



# Appendix B: PC Software Flow Diagram

Figure shows the flow of code with respect to threads i.e. when different threads are created.



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