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Abstract. We present an initial evaluation of a robotic arm for positioning a 3D echo probe during cardiac catheterization procedures. By tracking the robotic arm, X-ray table and X-ray C-arm, we are able to register the 3D echo images with live 2D X-ray images. In addition, we can also use tracking data from the robotic arm combined with system calibrations to create extended field of view 3D echo images. Both these features can be used for roadmapping to guide cardiac catheterization procedures. We have carried out a validation experiment of our registration method using a cross-wire phantom. Results show our method to be accurate to 3.5 mm. We have successfully demonstrated the creation of the extended field of view data on 2 healthy volunteers and the registration of echo and X-ray data on 2 patients undergoing a pacing study.

Keywords: 3D echocardiography, electrophysiology procedures, robotic arm

1 Introduction

Cardiac catheterization procedures are traditionally carried out under X-ray fluoroscopic guidance. Pure X-ray guidance has a number of disadvantages. Firstly, X-ray images are two-dimensional (2D) and it is difficult to locate the three-dimensional (3D) position and path of catheters. Secondly, X-ray images have little soft tissue contrast and it is difficult to interpret the anatomical context directly from these images. Also, fluoroscopy delivers a radiation dose to the patient and those carrying out the procedure. This can be significant for prolonged procedures and in paediatric cases. One of several approaches to overcome these limitations, and especially to reduce the X-ray radiation dose, is image fusion, for example, using hybrid X-ray and magnetic resonance (MR) imaging systems (XMR) [1]. XMR image

fusion is achieved using a combination of system calibration and real-time tracking to register 3D MRI-derived roadmaps onto X-ray images and can achieve an accuracy of 2mm. The 3D roadmaps can provide anatomical information such as heart chambers and vessels.

Another approach to overcome the limitations of X-ray only guidance is to introduce the use of echocardiography (echo) during cardiac catheterization procedures. 3D echo has high temporal and spatial resolutions, and the hardware is widely available in hospitals. Furthermore, using 3D echo can also overcome some limitations of MR/computed tomography (CT) based guidance [2]. Firstly, it can give clinicians real-time cardiac anatomical and functional information such as ventricular wall motion in real-time. Secondly, it can be used to compensate for patient motion such as cardiac, respiratory and bulk patient motion. All of those has made echo attractive for integration with X-ray to improve guidance especially in the field of cardiovascular intervention.

However, one of the major problems in using echo during cardiac catheterization procedures is the requirement for the steady and prolonged (typical procedure time is 3 to 4 hours) positioning of the echo probe in the vicinity of an X-ray radiation source. In this paper, we carried out a preliminary investigation into the feasibility of using a robotic arm to hold the 3D echo probe and acquire 3D echo images during cardiac catheterization procedures. We demonstrate how 3D echo images can be fused with live 2D X-ray images by combining robotic arm tracking, X-ray system calibration and echo system calibration. This solution is similar to the work by Rasche et al. [3]. However, we introduce a self-tracking and remote controlled robotic arm to position the 3D echo probe. This not only reduces the radiation to staff but also provides us with real-time tracking information about echo probe positions and orientation. In the following sections we outline the technical details of the robotic arm, echo to X-ray image registration, validation experiments and results.
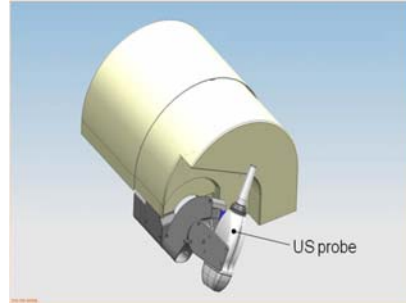
2 The Robotic Arm

The robotic arm was originally designed for tele-operation and has haptic feedback functionality. It contains two major parts: the master controller and the slave robot. As shown in Fig. 1a, the master controller is a Force Dimension Omega 6 and is commercially available (Force Dimension, Switzerland). It has 6 degrees of freedom: three translations and three rotations.

The slave robot was specially designed and constructed by Philips Applied Technologies. This holds the echo probe (Fig. 1b), senses the forces on the tip of probe and sends these forces back to the master controller. Three translations and two rotations are implemented for the echo probe. The rotation along the axis of probe itself is not implemented in this first prototype. The slave robot mounts onto a frame that attaches onto a standard catheter laboratory table. This frame allows the initial positioning of the slave relative to the patient and has minimal interference with the operation of the X-ray system. The slave robot has a 0.1mm translation tracking accuracy and 1 degree rotation tracking accuracy.

(a) The master controller   (b) The slave robot holding the echo probe

Fig. 1. The robotic arm system.

3 Echo to X-ray Registration

3.1 Tracking

Similar to the XMR tracking setting [1], we track the X-ray c-arm and X-ray table using an optical tracking system (Northern Digital Optotrak). As shown in Fig. 2, both the c-arm and the X-ray table are tracked by attaching an array of six infrared emitting diodes (IREDs).
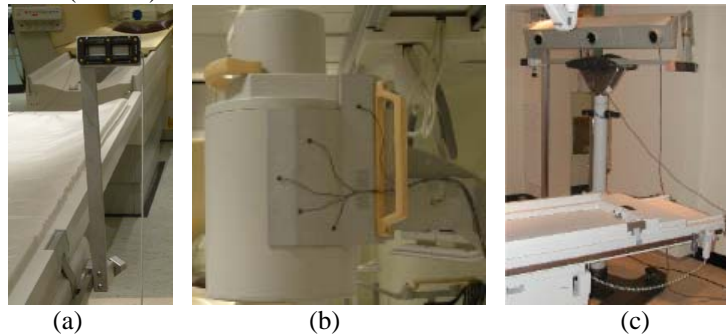

(a)   (b)   (c)

Fig. 2. (a) Tracking the x-ray table. (b) Tracking the X-ray C-arm. (c) The Optotrak tracking system.

3.2 X-ray system calibration

The X-ray system calibration establishes the transformation between Optotrak tracking space and 2D X-ray image space. It involves imaging a specially designed acrylic calibration object (Fig. 3a). This object consists of a half cylinder that can accept up to 120 interchangeable fiducial markers that can be visualized with X-ray imaging and located using an Optotrak pointer. The fiducial markers were automatically located in all the images and this data was used to compute the

relationship between the Optotrak tracking space and the X-ray c-arm local coordinate system, and the perspective projection parameters of the X-ray system.
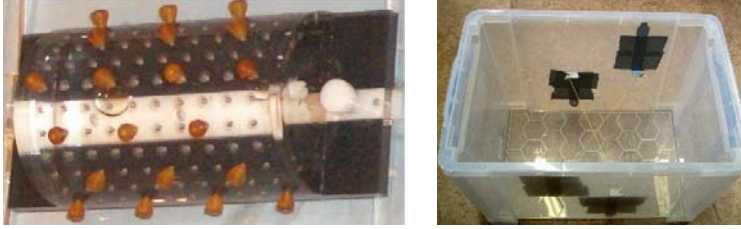
(a) The X-ray system calibration phantom. (b) The echo system calibration phantom.
Fig. 3. Calibration phantoms.

3.3 Echo probe calibration

We have previously developed a method to calibrate a 3D echo probe with the Optotrak system [4]. Our method uses a simple echo phantom (Fig. 3b) and acquires at least three 3D images while tracking the 3D echo probe. Intensity-based image registration algorithms are used to rigidly register these image volumes together. These transformations, along with the probe tracking information are used to find the calibration matrix which provides the transformation from echo image space to the local coordinate system on the echo probe. The simple echo phantom consists of a large PVC box filled with water with a rubber band cross in the centre.

Echo robotic arm system calibration is similar to echo Optotrak tracking system calibration. We only have to replace optical tracking matrices with robotic arm tracking matrices. The robotic arm tracking matrix $T_{Tip2Base}$ gives the transformation from probe tip to the base of robotic arm. The calibration matrix T_{US2Tip} we calculated from echo robotic arm system calibration which provides the transformation from echo image space to the local coordinate system in the tip of echo probe.

3.4 Robotic Arm Optotrak calibration

We establish the relationship between robotic arm coordinate systems and Optotrak tracking coordinate systems by Optotrak tracking the base of the robotic arm. We first rigidly attach the base of the robotic arm to the X-ray table through a specially designed mounting frame. Secondly, we rigidly attach three markers on the base so we can measure the 3D positions using an Optotrak pointer. Finally we can immediately calculate $T_{Base2OPT}$, which is the transformation from the local coordinate system in the base of robotic arm to the Optotrak tracking coordinate system.

3.5 Overall Registration

We are able to register 3D echo images with live 2D X-ray images by combining real-time robotic arm self tracking and Optotrak tracking. An overview of the registration

pipeline is shown in Fig. 4. T_{proj} is the X-ray projection matrix which is calculated from X-ray system calibration. $T_{CArm2OPT}$ is the tracking matrix of the X-ray C-arm. The overall echo to X-ray registration matrix is computed as:

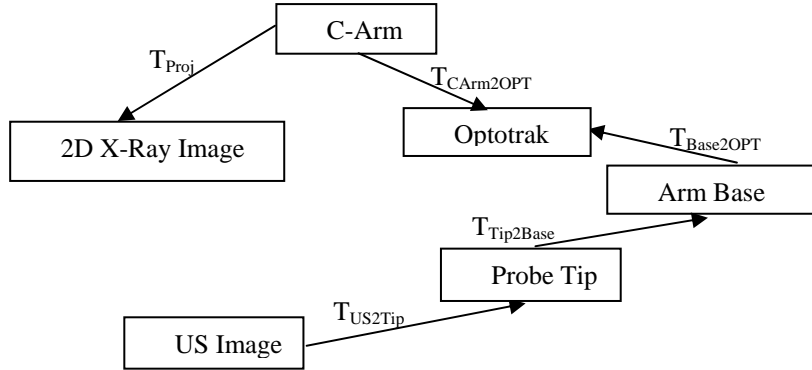$$T_{robot} = T_{proj} * T_{CArm2OPT}^{-1} * T_{Base2OPT} * T_{Tip2Base} * T_{US2Tip} \qquad (1)$$

Fig. 4. Registration pipeline.

Because the base of robotic arm can be moved to allow the echo probe access to different acquisition windows, we can update the $T_{Base2OPT}$ by measuring new 3D positions of the three markers on the base.

3.6 Optotrak tracking Registration

In order to compare the accuracy of registration using robotic self tracking T_{robot} with the registration using only Optotrak tracking, we propose a registration pipeline using only Optotrak tracking. First of all, we rigidly attach a tracking object that consists of 20 IREDs positioned in the form of a cross (Fig. 5) to the 3D echo probe so that the probe can be tracked by the Optotrak system. The overall registration matrix is computed as

$$T_{OPT} = T_{proj} * T_{CArm2OPT}^{-1} * T_{Cross2OPT} * T_{US2Cross} \qquad (2)$$

Where $T_{Cross2OPT}$ is the Optotrak tracking matrix for the IREDs cross and $T_{us2Cross}$ is the echo probe calibration matrix for Optotrak using the method described in [2].

Fig. 5. Tracking the 3D echo probe by using Optotrak system.

4 Experiments

4.1 Phantom experiment

The echo cross-wire phantom (Fig. 3b) was used to carry out a validation experiment to evaluate the accuracy of our registration methods. The X-ray system used in this experiment was a mobile cardiac X-ray set (Philips BV Pulsera) and the echo system was a Philips iE33 echocardiography system. The robotic arm holding the 3D echo probe was mounted onto the X-ray table. The echo probe was tracked by robotic arm itself.

We acquired 11 3D echo volumes and corresponding X-ray images of the cross-wire phantom. We manually picked two points on each line of the cross-wire to generate a single pixel/voxel width line in 3D echo image. The marching cubes algorithm was then used to create triangulated surfaces of the cross-wire. Fig. 6a shows the overlay of the echo line surfaces with the X-ray image. The error measurement of our registration is defined as the root mean square (RMS) error between the cross point of two lines in the echo image and the X-ray image. Errors were measured in the 2D X-ray image. Our results show a RMS error of 3.5mm (maximum error 4.2mm) in experiments using robotic arm self tracking. This compares favourably with an RMS error of 3.1mm (maximum error 4.4mm) using Optotrak tracking alone.

4.2 Volunteer study

The main aim of the 2 volunteer studies was to establish a suitable clinical protocol for using the robotic arm during cardiac catheterization procedures. In the absence of the X-ray images, we used the robotic arm self tracking to create an extended field of view echo volumes, which is created by using extended phase-based compounding technique [5] for large number of 3D echo volumes (Fig. 6b and 6c). Given an echo robotic arm system calibration matrix T_{US2Tip}, we can calculate the registration between two 3D echo volumes $T_{imgreg\,2to1}$ by using

$$T_{imgreg\,2to1} = (T_{Tip2Base1} * T_{US2Tip})^{-1} * (T_{Tip2Base2} * T_{US2Tip}) \qquad (3)$$
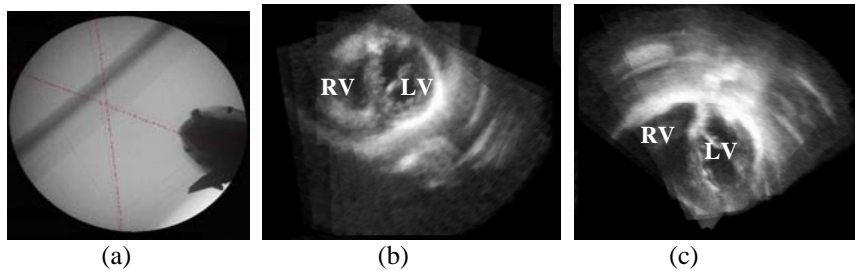

Fig. 6. (a) Phantom experiment. The transparent red lines are the 2D projection echo lines. (b)(c) Extended field of view images from multiple 3D echo data.

4.3 Patient study

We carried out two patient studies in the XMR suite in St. Thomas' Hospital, London. Both patients were undergoing pacing studies prior to pacemaker implantation for heart failure. In both clinical cases, the 3D echo probe was successfully positioned onto the patient's chest using the robotic arm (Fig. 7 and Fig. 8). A stable 4 chamber view of the heart was achieved from the apical window for several hours period (case1: 2.5 hours and case 2: 2 hours) with the requirement of only a single position alteration during this period. There was no discomfort to the patient and X-ray fluoroscopy could be acquired without the need to reposition the robotic arm. For each pacing mode, we simultaneously acquired the position of the pacing leads using sequential biplane X-ray images, the intra-cardiac electrical data, the left ventricular pressure, and the 4D echo data using the robotic arm. This provides very rich data to evaluate the outcome of the pacing modes.

For the data registration of case one, we manually segmented the myocardium of left ventricle (blue object) and electrical measurement catheter (pink object) and overlaid these onto one of the 2D X-ray images (Fig. 7c). By a visual inspection, our registration is well within our clinical accuracy requirement of 5mm for these types of procedure.

(a) clinical setup   (b) A zoom view of robotic arm   (c) Overlay
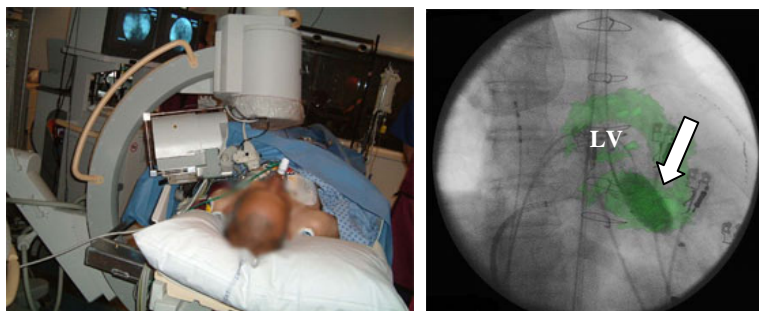**Fig. 7.** Case one. Electrical measurement catheter (arrow position)

Fig. 8. Case two. Electrical measurement catheter (arrow position)

For the data registration of case two, we directly use volume rendering of the 3D echo image and overlaid it onto one of the 2D X-ray images (Fig. 8). By a visual inspection, this registration is also within our clinical accuracy requirement of 5mm.

5 Conclusion and Discussions

Our initial evaluation of the robotic arm shows that the system can achieve a clinically useful registration accuracy of 3.5mm. Using volunteers we have established a safe working protocol for the robotic arm and also showed that the system can be used for the acquisition of extended field of view data which could be applied for roadmap creation. Our initial clinical studies demonstrated one of the potential uses of this system for acquisition of functional information during a pacing study. We are very encouraged by our initial results and aim to continue our evaluation by application of the system to further clinical cases. This type of system opens up the possibility of echo-based guidance of many types of cardiac interventional procedures.

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