"Virtual Touch": An Efficient Registration Method for Catheter Navigation in Left Atrium

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Abstract. In this paper, we present a left atrium registration system which utilizes a 3D intra-cardiac ultrasound catheter for *faster* (more than 700 times) and higher quality surface registration point collection than current systems and eventually improves the registration *accuracy* and *stability*. With better registration our a system can greatly improve the ablation catheter navigation system which is being used in many hospitals to guide left atrium endocardium ablation procedure.

1 Introduction

Recent years, researchers have developed image guided left atrium ablation systems which can automatically register the intra-operative heart shape data to the 3D or 4D model from pre-operative CT scans [1] [2] as well as commercially available Carto Merge system. These systems enable clinicians to navigate the catheter inside left atrium by seeing where the catheter is on computer monitor in real time. Such systems can greatly reduced the difficulty of left atrium ablation procedure, shorten the procedure time and improve its quality. The accuracy of such image guided system is mostly based on the accuracy of its registration. The registration needs clinicians to collect a few intra-operative registration points which clinicians know are on the left atrium endocardium. Then these registration points are used by an ICP [3] algorithm to find a transformation to the heart model coordinate system so that all the points sit on the surface of a left atrium model reconstructed from pre-operative CT scan. If we assume the heart model from CT scan is accurate, the qualify of the registration points determines the quality of registration and thus the accuracy of the whole navigation system.

Under current protocol of commercially available catheter navigation system Carto Merge, clinicians need to manually move a catheter with position sensor to physically touch the endocardium to capture a registration point, which is slow and tedious. The touch is verified by fluoroscopy images. As we know, fluoroscopy imaging device can not be turned on all the time, instead, it can take just a few snapshots. And in fluoroscopy images, heart wall is quite blurred and it makes clinicians hard to decide if the catheter is touching the heart wall. This uncertainty eventually affects the quality of registration points. Now some clinicians are using intra-cardiac ultrasound catheters to guide ablation catheters and verify the touch of ablation catheter to the heart wall [4] [5]. In this case, in addition to the ablation catheter, another ultrasound catheter is inserted into the left atrium. From the real time ultrasound images captured by the ultrasound catheter, clinicians can clearly see the ablation catheter touching the heart wall. The verification of touching is much better than with fluoroscopy images. This is the best scenario currently clinicians can have. But it doesn't improve the speed. To capture 50-60 registration points, a highly experienced clinician may need approximately 10 minutes. Usually in order to capture points which are well spread on the heart wall, more points are needed.

In this paper, we present a novel technique named "virtual touch" which employs an intra-cardiac 3D ultrasound catheter to collect high quality surface registration points at a speed of 700 times faster than current method. The key idea is, under current protocol, although we can see all the heart wall in ultrasound image, only the point that is physically touched by ablation catheter will be captured. With our "virtual touch", we capture every surface point we can see in an ultrasound image without physically touching it. When we move the ultrasound catheter and sweep the inner heart wall with ultrasound image plane, we can easily collect thousands of points on the heart wall which give the details of heart shape. It's like a 3D laser scan only replacing laser with ultrasound. And we argue that the quality of points captured by "virtual touch" is as good as if not better than those captured by physically touching the surface under the guide of ultrasound. More important, with thousands of surface points covering large portion of the left atrium, which is impossible for current systems, the registration's stability has been greatly improved. We will show in our paper that with our "virtual touch", the registration algorithm always find the correct registration independent of initial alignment.

In section 2, we will explain the technique in details. Results will be shown in section 3 with discussions. Finally we will conclude in section 4.

2 Method

The key idea of "virtual touch" is to "see" surface points in ultrasound image to capture them other than to move to and physically touch those surface points to capture them. To do this, our system first automatically detects inner heart wall pixels in ultrasound images and then reconstructs the 3D coordinates of these pixels. We will go through these steps one by one in the following sections.

2.1 Heart Wall Pixel Detection

When parameters of ultrasound machine are tuned accordingly, the heart wall can be seen clearly in ultrasound images. It makes the heart wall pixel detection easier. We first use canny edge detector [6] to detect edge pixels. We usually set the threshold of canny edge detector to a high level in order to collect only wall pixels with high confidence (clear edge). Because our whole algorithm is so fast, we can afford discarding points with even a little ambiguity. This is important to ensure the quality of our registration points.

Sometimes, other chambers of the heart are visible in the far side of the ultrasound image. To avoid including edge pixels of other chambers, we search along a bunch of beams sent out from the ultrasound catheter center as the red arrows shown in Figure 1 (a). When we search along one beam and hit one edge pixel, we accept it as a wall pixel, stop searching along the beam and switch to the next beam. Such searching strategy allows us to quickly include all the pixels that are on the wall of the chamber in which the catheter currently is and avoid most wall pixels belongs to other chamber, as shown in Figure 1 (c). More sophisticated contour detection methods could be used here. But we found this light-weight technique works just fine and it is very fast.

(a) (b) (c)

Fig. 1. Detect wall pixels: (a) the input image, red arrows sent out from the catheter center represent the direction we search for edge pixels: for each direction, we start from center and when we meet the first edge pixel, we will stop searching along that direction and move to the next direction. (b) the edge detected by canny edge detector. (c) Detection result: red crosses represent the accepted wall pixels. By searching along the red arrows, we can avoid edges from other chambers of the heart.

2.2 Intracardiac 3D Ultrasound

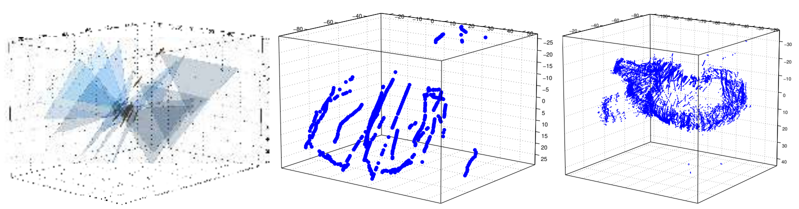
After we detected heart wall pixels in an ultrasound image, we need to reconstruct their 3D coordinates. A 3D ultrasound catheter can do the job. In our prototype system, we attached Ascension technology's Microbird tracking sensor onto a Siemens's Acuson intra-cardiac ultrasound catheter to build a 3D intracardiac ultrasound catheter. We use single plane phantom [7] to calibrate the 3D ultrasound catheter in a water tank. Temperature corrections has been done to all ultrasound images based on the speed of sound in water [8]. The calibration finds a matrix T and pixel size S_x, S_y, so that the 3D coordinates of any pixel *p(x,y)* in an ultrasound image can be calculated by:

$$P = M_i T \begin{pmatrix} xS_x \\ yS_y \\ 0 \\ 1 \end{pmatrix} \quad (1)$$

where M_i is the direct reading from the magnetic position sensor at the moment the ultrasound image is captured. It's a transformation matrix which gives the position and orientation of the position sensor attached to the ultrasound catheter. S_x, S_y is the size of ultrasound image pixel's width and hight in millimeter. T transforms the 2D pixel coordinate to the 3D coordinate of the position sensor and M_i transforms from the position sensor's coordinate to the transmitter's coordinate which is fixed during an operation. And eventually we get the 3D coordinate P.

2.3 "Virtual Touch"

As we can automatically detect heart wall pixels in ultrasound images and reconstruct the 3D coordinates of the wall pixels, the surface registration point collection procedure becomes much easier: Clinicians only need to navigate the 3D ultrasound catheter and make the image plane sweep the wall of left atrium. Our system will automatically capture the video output of the ultrasound catheter and detect wall pixels. The 3D coordinates of those pixels can be immediately calculated using equation 1 as shown in Figure 2. No physical touch is necessary: as long as the ultrasound image plane "touches" the heart wall. That's why we call this technique a "virtual touch".



(a) (b) (c)

Fig. 2. Virtual Touch: (a) Clinicians only need to move and rotate the 3D ultrasound catheter so that the ultrasound image plane can sweep large portion of the left atrium. (b) The system can automatically reconstruct the 3D wall points seen by ultrasound images. (c) An example of the heart wall points captured by our system. There are total 12781 points from 427 images.

After we collected registration points, an ICP algorithm will register the points to the left atrium model extracted from pre-operative CT scan. The registration will find a transformation from the magnetic tracking system's transmitter's coordinate to left atrium model's coordinate so that the distance from all registration points to the surface of the left atrium model is minimized. After registration, the ablation catheter which is tracked using the same magnetic transmitter can be visualized with CT left atrium model in real time to help clinicians to navigate it.

3 Results and Discussion

We tested the prototype system with phantom models built from real patient's CT scan. The phantom model's inside cavity has the same shape as the patient's left atrium. During the test the model was submerged in a water tank. We inserted the 3D ultrasound catheter inside the model and captured some wall points. The points then is registered to the 3D surface model which is used to build the phantom.

3.1 Registration Speed

During the test, we captured 427 ultrasound images within 3 minutes (at 2.5 frames/second) as shown in Figure 2 (c). Image processing (wall pixel extraction and 3D reconstruction) can be done in the same rate. And after 3 minutes, we successfully collected 12871 surface registration points (heart wall points). Comparing to currently move-and-touch protocol which usually needs about 10 minutes for 50-60 points, our method is more than 700 times faster.

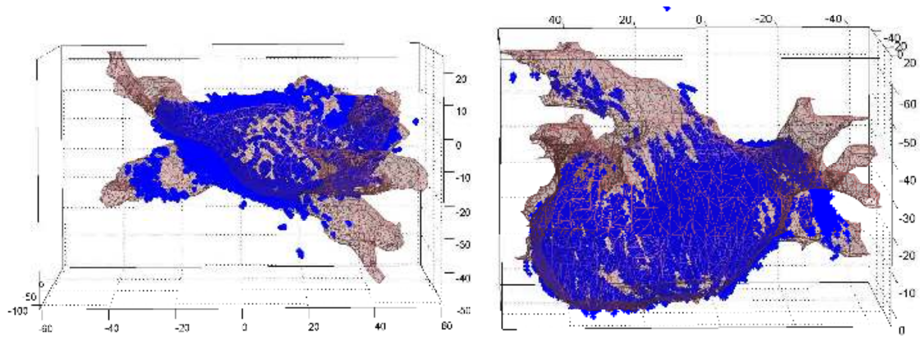
As ICP algorithm only takes seconds to find the registration using currently available workstations, the majority of time for registration process is spent to collect registration point. With 700 times faster, the whole registration process time will be greatly shortened. In our case, with 12871 surface registration points, the ICP algorithm still can be done around 2 minute. So the increase of time used by ICP to process more points is negligible comparing to the time saved to collect these points. Besides, during the operation, if the patient's position shifted a few millimeters, the registration already found will not be accurate anymore. With our system, it is so quick that clinicians can easily do another registration within 4-5 minutes and maintain the high accuracy of the current registration.

3.2 Registration Quality

We registered the surface points we captured by "virtual touch" to the 3D model from CT. The average distance from points to surface model after registration is 1.2143mm.

As we have stated in section 1 the registration quality is directly determined by the quality of registration points. With registration error around 1mm, we can see the points are of high quality. It is reasonable because under the best scenario, clinicians use ultrasound images to verify the touch of catheter to heart wall to collect surface registration points. Since the left atrium wall is not rigid, a touch may actually push the wall away from its original position. With our method, no physical touch happens so the wall points we captured will be as good as if not better than what clinicians can have using current technology.

As we can see in Figure 3, there are some outliers in our point set. Those are because of the speckle noise in ultrasound images. We expect there are tens of such outliers exist in our point data set. But given the total number of points in our point set is 12781, these less than 1% outliers can not divert the registration



(a) (b)

Fig. 3. Registration Result: average distance to surface model is 1.2143mm.

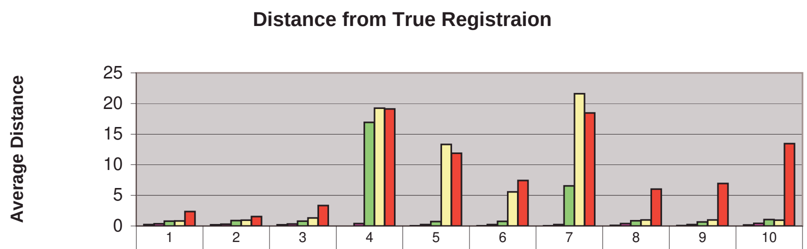
from the correct alignment. And with trimmed ICP algorithm [9], the effect of such outliers can be easily fixed.

3.3 Registration Stability

Most left atrium registration systems need a rough initial alignment of the surface registration points and heart model. Then the registration algorithm will start from this initial position to find the final alignment. Here we refer registration stability as given different initial alignments, how likely the registration will converge to the same final position. Registration quality tells us if an algorithm can find the correct registration and stability tells us how often it will find the correct registration. High quality registration algorithm with low stability is still useless.

We designed a stability test with our phantom data to prove the superior stability our "virtual touch" technique can achieve than other methods. We generated 10 random initial alignments: ±30 degree of rotation along x, y and z axis, and ±5 millimeter translation from ground truth registration. And we sub-sampled our 12781 surface registration points down to four other point sets each having 1278, 127, 63 and 31 points. As we know, clinicians using Carto Merge system in surgery usually collect around 100 - 150 registration points, which is similar to our point set with 127 points. We use these five sets of data to do registration from all 10 initial alignments. After each registration, the registered points are compared to the ground truth registration found by the full point set from a manually selected initial alignment. The criteria is the average distance from registered points to the corresponding points in the ground truth registration. Result are shown in Figure 4. All distances are in millimeter.

As we can see with the full point set, the average distances of registered points from all 10 initial alignments are all very small. It means that they all converge to the ground truth registration. With 1278 points, uniform convergence to ground truth is still achieved. But when it reaches 127 points, which is the usual number of points clinicians collect in practice, 2 initial alignments lead to



	1	2	3	4	5	6	7	8	9	10
12781 Points	0.239244	0.189292	0.200301	0.011323	0.036552	0.040491	0.025791	0.086031	0.052759	0.167314
1278 Points	0.353782	0.299789	0.339517	0.402698	0.231462	0.231047	0.231047	0.390771	0.239915	0.409869
127 Points	0.796582	0.87	0.782215	16.91233	0.734631	0.754926	6.534909	0.844455	0.662114	1.043424
63 Points	0.827056	0.947734	1.301756	19.24869	13.32786	5.566431	21.60325	0.967121	0.968104	0.932957
31 Points	2.353648	1.547783	3.323919	19.12419	11.87948	7.427406	18.44368	6.032702	6.93717	13.45132

Fig. 4. Stability Test Result

wrong registrations. With fewer points like 63 or 31, four or all initial alignments lead to wrong registration.

With systems like Carto Merge, clinicians usually collect 100-150 registration points because to collect more points will take too much time. As shown in our test, with 127 points, 20% of the initial alignments failed to converge to correct registration, clinicians have to have a very good initial alignment to ensure correct registration. In Carto Merge, initial alignments are found by landmark points (must not be less than 3). Clinicians need to tell the system exactly where these landmark points should be on the CT left atrium model. The issue is: clinicians are not supposed to know exactly where the catheter is inside the heart. It's Carto Merge's job to tell where it is by registering the points to the CT model. Now clinicians must provide such information to Carto Merge before it can tell where the catheter is. Hence there is no guideline as where in the left atrium clinicians should collect landmark points. Then it is likely that these landmark points will be of low precision and may give the registration algorithm a very bad initial alignment. Eventually, it has a high probability that the final registration could be wrong. Very sadly, in reality we do not have ground truth registration to tell if a registration is wrong or right. Clinicians have to believe it is correct.

But with "virtual touch", to capture ten thousand points will not take 3 minutes. And our experiment clearly shows that with 10,000 points, the correct registration can be found independent of initial alignments. With such superior stability, clinicians can be very confident about the registration found with "virtual touch".

4 Conclusion and Future Work

In this paper, we present a novel fully automatic left atrium registration method using "virtual touch". It is very *fast*, very *accurate* and very *stable*. In our phantom model experiment, we showed that our prototype system can collect high quality surface registration points more than 700 times faster than current methods. The registration error with our system is around 1.2mm. Also we showed that our registration can be independent of initial alignment because it can collect enough points to reveal even the finest topological details of left atrium and lead the registration to the true alignment. Besides all those benefits, the system is easy and cheap to build. Comparing to fluoroscopy imaging devices, our prototype system can do the job much better yet cost much less. It can be easily deployed to hospitals with minimum modification of current available devices.

Animal tests of this new technique has been scheduled. In the future, we will develop faster yet more sophisticated automatic heart wall pixel detection algorithms to minimize the effect of speckle noise in ultrasound images. Also a post-process algorithm could help to eliminate outlier points.

Based on this "virtual touch" technique, many before impossible tasks now become possible. Researchers can use our technique to collect thousands of surface points of left atrium and use part of them as registration point set and rest as test set to evaluate new registration algorithms. We realize that because heart is non-rigid and adjacent to other moving organs, the shape of left atrium changes during operation from what it was during CT scan. With "virtual touch", we can collect enough points to capture even the finest topological details and these points could be used to modify high-resolution models from CT scan and result a better navigation system for left atrium ablation procedure as well as in other heart chambers.

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