An Efficient Algorithm for Real-time Catheter Tip Detection in a Virtual Reality of Electrophysiology Study

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Abstract

A virtual reality environment to visualize and manipulate 3D spatial human heart model and catheter in real-time was developed recently to interact with actual catheter to conduct electrocardiogram simulations. Since in the captured images, the catheter is loop-crossing, irregularly shaped, and often broken by the myocardium, it is difficult to catch the catheter tip in real-time. This paper describes an efficient algorithm for real-time catheter tip detection used in the simulator. After binarizing the catheter images and removing the noises, the width of the catheter is thinned to one pixel. In order to remove the reflection and refraction of light, the pixels of the whole catheter are labeled, and the feature patterns are extracted by using LUT method before detecting the catheter tip. Efficient algorithms are used to connect the broken parts and detect the loop crossings. The experimental results show that the average accuracy is above 79%. We keep the accuracy while optimizing the algorithm with higher performance.

1. Introduction

The rate of death by heart disease, such as coronary artery disease, is very high in Japan, which holds the second place to cancer according to the statistical information of the Ministry of Labor and Welfare [1]. Recently, cardiac catheterization has been used for the diagnosis of heart disease, instead of a chest incision [2]. It is very difficult to train doctors with cardiac catheter ablation techniques [3] [4]. Therefore, we are developing a catheter simulator using a 3D heart model to improve doctors’ skills. The simulator enables doctors to measure the electricity of the heart, especially some particular parts, such as high right atrium (HRA), bundle of His (HIS), and right ventricular apex (RVA). In addition, doctors confirm how electricity is transmitted within the heart by comparing normal hearts and abnormal hearts using the electrocardiogram [7].

Virtual reality is a way for humans to visualize, manipulate and interact with computers and extremely complex data. Virtual reality is very useful since it can generate a 3D spatial environment in which humans can participate in real-time [5]. It is a novel approach for us to apply the virtual reality technologies into medical and surgery fields. This paper describes the development of the simulator and the implementation of algorithms to detect coordinates of catheter tip for assisting to measure the patient’s electrocardiogram. When the hardware parts of the simulation system are setup, the coordinates of heart cells and catheter tip should be obtained from the hardware part via cameras, and then the 3D heart cells and catheters should be visualized as X-ray picture and displayed on screen in real-time.

The catheter tip detection procedure is in direct contact with the hardware. By capturing the model image, the shape of the inserted catheter is recognized and the coordinates of its tip are identified in real-time. During the simulation, it is difficult to identify an image of the catheter tip because the catheter is irregularly shaped and it moves quickly. Therefore, methods used by M. Marutani et al. [6], which recognizes the hand pose by using the contour of the hand area, is less information in detecting the tip. In the simulator, the length of the catheter is used to trace the catheter tip. Before that, a thinning method is used to reduce the catheter line...
to the width of one pixel. Therefore, the calculation processing can be reduced largely. Other difficulties are shown in Figures 6 and 7, such as that the catheter shape on the image is often broken by reflection and refraction, loop-crossing, etc. In this paper, we propose algorithms to solve these problems. The images are binarized with threshold obtained in the experiment [9]. Noise reduction is implemented to reduce obscurness of the disconnection and the roughness when transform from the binarized image to the thinning image. Next, the labeling is done in eight neighborhoods and the object is made.

The organization of this paper is as follows. Section 2 gives the procedures of catheter tip detection. Algorithms for feature pattern extraction from catheter image is given in Section 3. Section 4 shows the results and discussions. Section 5 gives the previous work. Finally, we conclude our work in Section 6.

2 The Procedures of Catheter Tip Detection

In the 3D virtual X-ray camera system, pictures are captured from each camera in real-time [8]. Motion detection algorithms are used to find the coordinates of the catheter tip in each picture. Then 3D coordinates are generated for both the catheter tip and the heart model and sent to other systems such as virtual X-ray monitor and virtual ECG monitor. Processing that detects the catheter tip has two main stages. One stage is preprocess, includes binarization, noise reduction, and skeletonization and the next stage is pattern extraction.

The catheter images are calculated from the comparison between images with and without catheter. To detect the catheter tip, we first need distinguish the shape of the catheter. There are some problems when the catheter tip is extracted. In the images, normally the width of the catheter tip is more than one pixel. At the bend point, it is difficult to judge the expected moving direction. So it is expensive to calculate and analyze the images without any preprocess. Also, there are noises in the images because of the refraction of light.

Thinning is a method of changing the width to one pixel in image processing. Before thinning, the image is binarized using global threshold method [11]. Threshold value is set in this stage. When a catheter goes straight, the inside and outside of the perimeter are the same. However, when the catheter has the bends and the crosses, the inside and outside of the perimeter are not the same. Therefore, Hilditch algorithm needs to be used here for thinning the catheter [10].

Due to the refraction of light, the image of the catheter might disappear while taking a picture of the heart model. Labeling is utilized after the thinning method to overcome this limitation. Each catheter pixel is labeled as a number at the connected pixels so that we can easily conduct various processings, such as feature pattern extraction.

3 Algorithm for Feature Pattern Extraction

After labeling the pixels of the catheter in the images, the feature patterns need to be extracted before detecting the catheter tip. In order to find the catheter tip efficiently, we implement this algorithm based on Look-up table (LUT) method [12]. LUT is an array with 512 elements where the subpixel of the binary image is a 3×3 matrix (rendered as white box or black box of 9 neighborhood pixels). The feature patterns are as follows. Point pattern is shown in Fig. 2(a), tip in Fig. 3, triple bifurcation in Fig. 4, crossing in Fig. 2(b), and others in Fig. 2(c), respectively. All these figures show the feature patterns together with their identifying numbers.

First, we create a lookup table which has all patterns of 3×3 subpixel as in the table shown in Figure 1. Each pattern is identified by an identification number from 0 to 511. The number is calculated by the following equation 1.

\[ N = S \cdot F \]  \hspace{1cm} (1)

where \( N \) is the identified number of the pattern of the subpixel, \( S \) is the matrix of the subpixel pattern where pixel is 1 and background is 0, and \( F \) is a filter shown in Fig. 2.

\[ F = \begin{pmatrix} 256 & 32 & 4 \\ 128 & 16 & 2 \\ 64 & 8 & 1 \end{pmatrix} \] \hspace{1cm} (2)

\( LUT(n) \) identifies a specific property of the pattern of the subpixel \( n \). The pattern code is set as follows. \( LUT(n) = 1 \), when subpixel \( n \) is one
Figure 1. The look up table of all subpixel pattern.

Figure 2. (a) Point (b) Crossing (c) Others

Figure 3. Tip.

Figure 4. Triple bifurcation.

pixel; \( LUT(n) = 2 \), when subpixel \( n \) is a tip; \( LUT(n) = 3 \), when subpixel \( n \) is triple bifurcation pattern; \( LUT(n) = 4 \), when subpixel \( n \) is crossing pattern; \( LUT(n) = 0 \), when subpixel \( n \) is other pattern.

\[
LUT(16) = 1 \\
LUT(17) = LUT(20) = \cdots \\
= LUT(48) = LUT(144) = 2 \\
LUT(284) = LUT(113) = \cdots \\
= LUT(58) = LUT(184) = 3 \\
LUT(186) = LUT(341) = 4 \\
LUT(others) = 0
\]

Above, by filtering the preprocessed image with \( F \), the feature patterns on the image are detected, and then we get Equation 5.

\[
M_{LUT} = LUT(I \odot F)
\]

where \( M_{LUT} \) is the image matrix of the detected feature points, \( I \) is a preprocessed image matrix, \( n \) is the height of the image, \( m \) is weight of the image, \( P_{ij} \) is a pixel at \((i, j)\) on the image \( I \), and \( p_{ij} \) is the pattern code of \( P_{ij} \).

Using the feature pattern, it is easier to find the catheter tip. Tracing the catheter line in the same label from the start point, the system finds the innermost tip from the start point on the same label in locus distance. During tracing, pursue in the direction of movement first if the tracing point is crossing pattern. If going through the crossing point again, the line will be overlapped. Otherwise, the crossing point is the bifurcation point, then try to find the farthest way from the crossing point. Repeating above, the system can detect the farthest point from the start point on the image. The final detected farthest point is the catheter tip.
4 Results and Discussion

The experiments were conducted on Pentium(R)4 machine with 2.40 GHz CPU and 1.00 GB RAM. The catheter ablation simulator works successfully and the virtual X-ray monitor display is shown in Figure 5. At random, the catheter tips are moved from the starting point to randomly selected locations, such as HRA, HIS, and RVA [15].

Table 1. The accuracy results of catheter tip detection

<table>
<thead>
<tr>
<th>Dist</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ≤ d &lt; 10</td>
<td>Num</td>
<td>%</td>
<td>Num</td>
<td>%</td>
</tr>
<tr>
<td>0 ≤ d &lt; 10</td>
<td>31</td>
<td>81.58</td>
<td>28</td>
<td>67.57</td>
</tr>
<tr>
<td>10 ≤ d &lt; 20</td>
<td>3</td>
<td>7.89</td>
<td>4</td>
<td>10.81</td>
</tr>
<tr>
<td>20 ≤ d &lt; 30</td>
<td>2</td>
<td>5.26</td>
<td>3</td>
<td>8.11</td>
</tr>
<tr>
<td>30 ≤ d &lt; 40</td>
<td>0</td>
<td>0.00</td>
<td>2</td>
<td>5.41</td>
</tr>
<tr>
<td>40 ≤ d &lt; 50</td>
<td>0</td>
<td>0.00</td>
<td>1</td>
<td>2.70</td>
</tr>
<tr>
<td>50 ≤ d</td>
<td>2</td>
<td>5.25</td>
<td>2</td>
<td>5.41</td>
</tr>
</tbody>
</table>

First of all, we conducted experiments on accuracy of the catheter tip detection. Three types of the images were taken into considered. Type A has 240×320 high contrast images, type B has 240×320 normal images, and type C has 600×800 normal images, respectively. The number of all images is 110. The accuracy results are shown in Table 1. In Table 1, the results of three different types are compared with distances d, which is the distance between the extracted catheter tip and the real catheter tip. The results of d < 20 are considered as high accuracy because smaller d means high percentage while larger d means low percentage. Here, highly accuracy has been achieved using LUT method. For example, when d < 20, 79.09% high percentage of catheter tips is detected correctly in average. The accuracy is same as using FLAG method in previous work.

The results indicate that larger images have more detection errors. The accuracy percentage of d < 50 is 81.58% for type A, 67.57% for type B, and 57.14% for type C, respectively. As mentioned above, type A images are high contrast small images, and type B images are normal small images. It is obviously that catheter tip in high contrast images are easier to be detected.

The results with d > 50 are incorrect detections. It is due to the incomplete of noise reduction and the incorrect threshold value. When performing the pre-processing, the images may still have some noises as lack of complete noise reduction. If the noise is not completely removed, it may mislead the catheter detection. In the above algorithm, we use the same threshold value for both large images and small images. From Table 1, it is clear that larger images have more incorrect detection cases for the d > 50 cases if using the same threshold value. While the threshold value may be different in different images, it is necessary to set the threshold value as a function of the size and/or contrast of images.

Previous work on pattern extraction using FLAG method [13] is included to compare with the LUT method [14]. Table 2 shows the comparison of the processing time among these algorithms. FLAG method is, however, unduly slow to process it. LUT method is still somewhat slow to be used in real-time. To improve the speed, we set 27 as the threshold value experientially and skip the dilation morphing process. Most noises are erased when this threshold value is set. From Table 2, we can see that the processing time is drastically reduced to its one seventh.
Figure 6. The image is often broken by reflection and refraction

Figure 7. The catheter is crossing itself by looping.

Table 2. The average time comparison of processing a image at Intel Pentium4(R) 2.00Ghz

<table>
<thead>
<tr>
<th>Image size</th>
<th>800×600</th>
<th>320×240</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLAG method</td>
<td>75 s</td>
<td>15 s</td>
</tr>
<tr>
<td>LUT method</td>
<td>15 s</td>
<td>2 s</td>
</tr>
<tr>
<td>Optimized LUT method</td>
<td>3 s</td>
<td>0.3 s</td>
</tr>
</tbody>
</table>

5 Previous Work

Previous work is based on the status of each pixel’s eight neighborhood pixels. To identify coordinates that bend or rotate in the image, the state is stored to array variable FLAG. The FLAG is set to the index of the bends and crosses. Detailed algorithm can be found from Ref. [13].

There are three possible patterns. One case is that FLAGS are all 1, which means bend does not exist. It scans in order from the catheter injection, and the final coordinate is assigned as the catheter tip. The second case is that one bend point exists. The FLAG preserves the value 2. It scans to the bend point, and judge the catheter tip by the distance from the bend point to final coordinates. The third case is that over two bend points exist. The previous bend point is replaced with the finding bend point when the pixel while measuring the distance after the first bend point discovers the second point. The first bend point needs not be considered. Therefore, repeating this process, the catheter tip each case is assigned.

However, there are gaps in the catheter line of the images. It scans the pixel in the nearest area. After discovering the shortest pixel, the catheter tip is acquired by substituting the coordinate of the catheter tip for the shortest pixel.

This algorithm was implemented and tested in our experiments. The results show that its accuracy is good. However, it takes much more time than we expect.

6 Conclusion

A virtual reality environment was developed as the fundamental of the simulation systems for electrophysiology study and catheter ablation. In the system, a virtual X-ray camera is connected with the hardware system to capture the coordinates of the the catheter tip in real-time. The catheter is irregularly shaped and it moves quickly. Also, there are noises in the images because of the infraction and refraction of light. In this paper, some novel algorithms are proposed to detect the coordinates of the catheter tip.

After binarizing the catheter images and removing the noises, we thin the catheter to the width of one pixel in the image preprocessing. In order to re-
move the reflection and refraction of light, we label
the catheter pixels and extract the feature patterns us-
ing LUT method before detecting the catheter tip. Ef-
ficient algorithms are used to connect the broken parts
of the catheter and detect the loop-crossings of the
catheter. The experimental results show that the av-
erage accuracy is above 79%. Also the algorithm is
optimized to utilize fewer resources and have higher
speed.

Future tasks include accuracy enhancement and
system performance enhancement. Also, the simu-
lator displays only trajectory of the catheter tip be-
cause it gets only the coordinates of the catheter tip. It is also
required to complete the trajectory of whole catheter in
real-time in future work.

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