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Abstract. The use of 3-D patient-specific anatomical models in combination with an electromagnetic (EM) catheter tracking device has become the standard for guidance of pulmonary vein (PV) ablation. The anatomical model, derived from CT/MR-images, has to be registered to the EM tracking system by means of a time consuming procedure and the use of these EM systems comes with a high associated cost.
We present a method for determining the ablation catheter tip position with respect to a 3-D model, without the need for an EM tracking device. Using only biplane fluoroscopy, the ablation catheter tip can be tracked and visualized in conjunction with a patient-specific 3-D anatomical model. Tip tracking is realized by a discrete image pattern tracking technique which is regularized using a Kalman filter. The method was integrated in a software suite for image guided treatment of catheter ablation procedures to test its usability in a real clinical setting.
An accuracy evaluation was performed on several image sequences, recorded during actual procedures. The tracking method is able to track the 2-D location and reconstruct the 3-D pose of the tip for several sequences of images with an accuracy of 1.7 mm. During several procedures the tracking approach was tested and performed well over periods of several minutes after which reinitialization was needed.
The proposed approach can offer an alternative for EM tracking systems for integrated 3-D visualization of the ablation catheter tip and a 3-D model. Since neither specific hardware nor dedicated catheters are needed, the associated usage cost of this approach is much less compared to EM tracking systems.

1 Introduction

Treatment of patients suffering from atrial fibrillation by catheter ablation consists of applying a lesion at the ostia of all PVs. The procedure starts by assessing the correct ablation target and subsequently guiding a catheter to the planned target ablation site to apply radio frequency (RF) energy.

This intervention has evolved substantially in the past years. The most important changes are the introduction of catheter tracking systems like Carto (Biosense Webster Inc., CA, USA) and Ensite (St Jude Medical, MN, USA)

and, more recently, the use of preinterventional 3-D CT/MR models in combination with the former tracking systems. The use of 3-D cardiac models has offered very detailed anatomical information to plan and guide the procedure. Nevertheless, this approach has a number of drawbacks. There is a substantial catheter and system cost compared to the conventional approach and the registration procedure that is needed to relate the 3-D model to the tracking space, is error-prone and time-consuming.

Alternative solutions [1, 2] have tried to overcome these limitations by immediately merging the 3-D models with fluoroscopic imaging thereby obviating the need for expensive tracking systems. These approaches, however, lack the ability to show the ablation catheter tip in relation to the 3-D model which is important for determining if the planned trajectory is properly followed. As an extension to these approaches we propose a method for image-based catheter tracking to obtain the 3-D pose of the ablation catheter tip.

Previous work on image-based tracking of catheters has been focusing mainly on the tracking of guide wires [3, 4] in the treatment of arterial disease. Tracking of a guide wire differs from tracking an ablation catheter because the former exhibits no specific features and can move almost randomly in the image. The ablation catheter in the treatment of atrial fibrillation remains in the same region of the image for a relatively long time and motion is limited to a continuous line. Nevertheless cardiac and respiratory motion could cause sudden jumps in the position. Furthermore, it has not been shown that these approaches for tracking guide wires can meet the real-time constraints for interventional guidance yet. Therefore it is not straightforward to extend these methods for the purpose of ablation catheter tracking.

Instead, we propose to use a fixed template-based registration method in conjunction with a Kalman filter to track the catheter tip in a series of biplane fluoroscopy images. Calibration information then enables the 3-D reconstruction of the catheter tip which subsequently can be visualized together with a 3-D patient specific model and the planned target ablation trajectories. In this paper we present the method, provide an initial accuracy evaluation and report initial clinical experience.

2 Method

2.1 Algorithm

Conventional setup for AF treatment The clinical setup consists of a biplane fluoroscopic system which is linked to the dual channel frame grabber that is used to record and store the fluoroscopic images. During the intervention a rotational angiography is acquired from which a 3-D surface model is derived using in house developed software. Registration of the 3-D model was obtained by a point-based registration method similar to [1, 2] using catheter electrodes as reference markers.

The catheter used for ablation of the PV's typically consists of a tube with multiple radio-opaque electrodes of which the largest is located at the tip. This
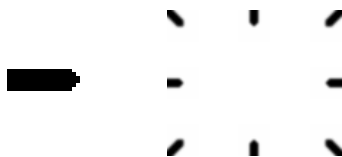
Fig. 1. Left: standard template for the projection of a catheter ablation tip. Right: Limited subset of all possible orientations of the template. In this case we consider 8 possible orientations.

tip has a length between 4 and 12 mm and diameter of around 2 mm (7F) and delivers the RF energy. The resulting lesion size is in the order of 1 cm [5]. During AF treatment the catheter is visualized by alternating biplane fluoroscopy at 3 frames per second (fps), implying that images are acquired in one view angle only at a specific time. Since the ablation tip appears in the image as a dark rectangle with a rounded end, we propose a tracking method that attempts to register a standard template of the ablation tip to each fluoroscopic image. This task is described in the following section. The resulting 2-D tip position is then filtered by a Kalman filter to obtain a smooth movement of the tip position and orientation, and to increase tracking speed by providing a good estimate of the next position (see Section 2.1).

Discretized template based registration The ideal projection of the ablation catheter tip in the fluoroscopic image can be computed by projecting a cylindrical model with a rounded edge using typical fluoroscopic camera parameters. Approximating the projection by an orthographic model, all possible projections of the cylinder will be an infinite number of rounded rectangles which all have a different orientation.

Instead of performing a registration of the catheter to the acquired images I_k with 4 degrees of freedom, we propose to limit the infinite number of poses to a well distributed, discrete set, similar to the work of Hoff *et al.* [6]. By using a discrete set, we can obtain a fast registration method in which all possible templates can be precomputed. Empirically, we found a subset of 8 orientations, as depicted in Figure 1(Right pane), a good trade-off between speed and accuracy.

Localization of the tip is then performed by computing the normalized cross correlation between all templates at all image locations and selecting the pose with the highest value. The implementation of a Kalman filter limits the search region and enables a larger reduction of complexity by withholding the most likely template orientations only.

Kalman filtering To reduce the search region and select the most likely template orientations, we propose to use a Kalman filter. A Kalman filter is a recursive state estimator that uses a prediction and update phase to compute the

state of a system. In our approach it estimates the 2-D position and in plane-orientation of the ablation tip. Therefore, the state vector X of the Kalman filter holds the image position $p_k(x_k, y_k)$ and the orientation of the catheter tip stored by its sine and cosine. The prediction of the state vector is computed by a unit transform. Furthermore we assume a process noise and measurement noise of respectively 3 pixels and 1 pixel for the position and 0.1 rad and 0.1 rad for the orientation.

During tracking we can use the prediction step of time $k-1$ to obtain an initial estimate of the pose $(\hat{p_k}, \hat{d_k})$ of the catheter tip in time k. The registration, as described in the previous section, can then be conducted in a region of I_k around $\hat{p_k}$ and with templates corresponding to orientations that are near $\hat{d_k}$. The selection of the templates is based on the state covariance which is stored and updated by the Kalman filter as well. The position and orientation corresponding to the highest correlation value is subsequently used as observation of time k for the Kalman filter if the correlation value is above a threshold. Hereby the state vector can be updated and the new state values for the position of the tip can be used for rendering (see Section 2.1). We call this Method 1.

Additionally, there is the possibility to perform an optimization of the position using the exact orientation: after updating the Kalman filter, d_k can be used to compute a template which is very close to the actual orientation of the tip. Using this template, the search can be repeated once to refine the position of the catheter tip. This improved estimate is obtained at the expense of additional computation time which may not be available always. We call this Method 2.

Both methods are implemented in Matlab$^{\text{TM}}$. The routines can be addressed from control software that provides integrated rendering of the model and the catheter tip.

Clinical use The tracking approach, described above, results in a estimate of the ablation catheter tip position for all newly acquired fluoroscopic images. In a biplane system, this returns $p_{k-1}^{RAO}, p_k^{RAO}, p_{k+1}^{RAO}, \ldots$ and $p_{k-1}^{LAO}, p_k^{LAO}, p_{k+1}^{LAO}, \ldots$. Using the calibration information of both the LAO and RAO view, one can compute the 3-D point P_k belonging to (p_k^{RAO}, p_k^{LAO}).

This 3-D point P_k can not only be rendered over the fluoroscopic images to verify correct tracking but also, and more importantly, can be shown in conjunction with a patient specific 3-D model and the planned target ablation sites. The latter can be realized through presentation in an endocardial view. An example of such an integrated rendering is shown in Figure 4.

2.2 Evaluation

The presented approach was evaluated both on image sequences recorded during atrial fibrillation interventions and during actual interventions. The former evaluation was conducted to evaluate the accuracy and robustness in a controlled setting while the latter serves to evaluate the usability of the tracking approach in a real clinical situation.

During 8 interventions we recorded 14 sequences of fluoroscopic images at 3 fps that were part of the standard procedure of treatment. Both RAO and LAO view images (yielding 28 image sequences in total) were acquired during actual ablation. Special care was taken to acquire sequences in which there was prominent catheter tip movement. Different veins were imaged in sequences with varying length between 10 and 100 seconds. In addition to the ablation catheter also a LASSO^{TM} catheter was visible.

For each of the image sequences, we manually marked the ablation catheter tip in each of the images. Subsequently we used Method 1 and Method 2 to compute the catheter tip location for the entire sequence. We recorded 2-D tracking error, 3-D tracking error and the computation time. The 2-D tracking error is defined as the difference between the manually marked position and the one obtained by either of both tracking methods. The 3-D tracking error is computed as the difference between the reconstructed 3-D point from the manually marked points of the most recent RAO/LAO image pair and the reconstruction of the 2-D points as determined by the tracking methods. Due to the alternating biplane acquisition scheme, the ground truth for 3-D error analysis will not always reflect the true 3-D location of the catheter tip since it can be based in part on earlier acquired 2-D images. It represents rather the best 3-D estimate given the most recent data at a specific time.

Finally, a qualitative assessment was made of the usability of this method during clinical routine on a limited number of procedures.

3   Results

3.1   Accuracy results

Figure 2 shows a typical trajectory of the catheter tip by the result obtained by the manual marking, Method 1 and Method 2. The bottom panes show the error obtained in each time step. Method 2 with an average computation time of 0.12 ± 0.04 sec/image requires about 20% more computation time than Method 1 $(0.11\pm0.04$ sec/image). However, both methods remain well below 0.33 seconds which is the maximum available time when imaging at 3 fps.

In 5 of all 28 sequences tip (or 18%) tracking temporarily failed due to another neighboring visible structure, like the LASSO catheter. No dependency was found toward a specific view or the sequence length. In all sequences the tip tracking continued to track the tip well after the other structure disappeared from the field of view.

The histogram of resulting error for all sequences is displayed in Figure 3 for both methods and for the RAO and LAO view. The average error is 3.1 ± 4.2 and 3.0 ± 4.2 pixels for Method 1 and Method 2 respectively. Because of the relatively high increase in computation time to obtain no significant increase in accuracy we opt for using Method 1. Finally, the 3-D error is visualized in the right pane of Figure 3 and shows that the average 3-D error is 1.67 ± 2.60 mm and 1.66 ± 2.59 mm for Method 1 and Method 2 respectively which both are sufficient for usage during AF ablation therapy.
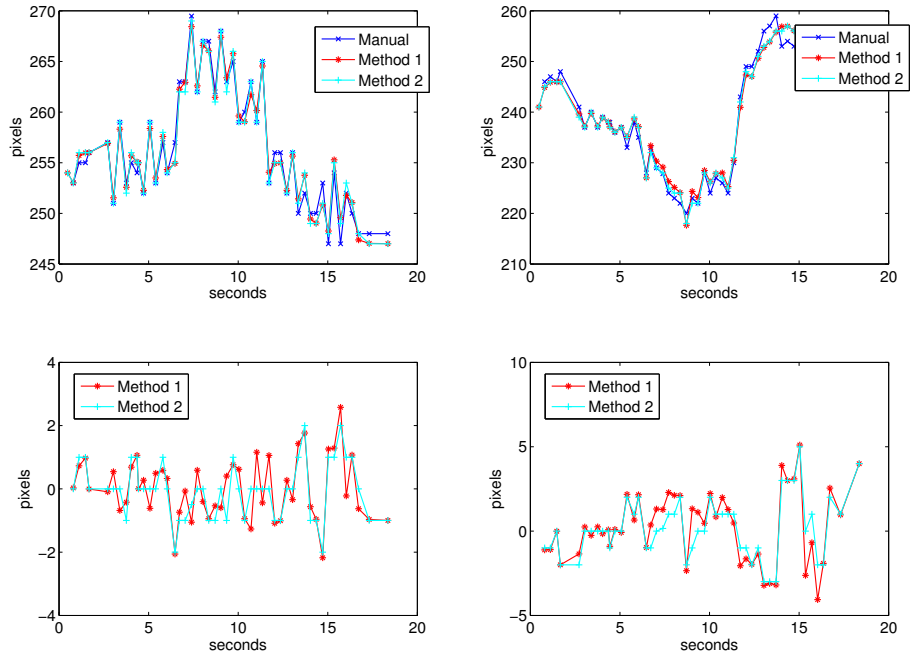
Fig. 2. The top row shows an example trajectory of the ablation catheter tip in an RAO view for both x and y axis (left and right pane) and the results obtained by applying Method 1 and Method 2. The bottom row displays the difference between the manual marked trajectory and the ones obtained by both methods.
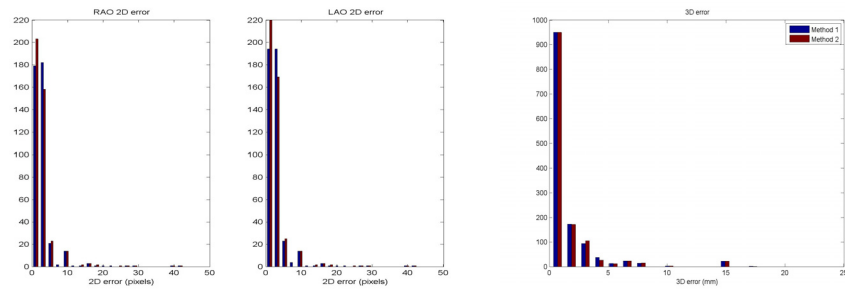

Fig. 3. Histogram of both the 2-D (left, RAO and LAO) and 3-D (Right) errors of all 14 sequences. These values also include the temporary mismatches which occurred in 18% of the sequences but which were automatically resolved by the methods.

3.2 First clinical experiments

During 5 cases of atrial fibrillation we applied Method 1 and showed the reconstructed catheter tip integrated with a 3-D patient-specific model. We experienced that the method was able to track the catheter tip up to several minutes after which a manual correction, often only needed in one view, could correct tracking. Mismatches also occurred because of the alternating fluoroscopy (applied for radiation reduction) caused time mismatches between RAO and LAO. An endocardial view (see Figure 4) was offered to the electro-physiologist who found it useful as a feedback to aid in the steering of his catheter and to evaluate how well he followed the planned target ablation sites.
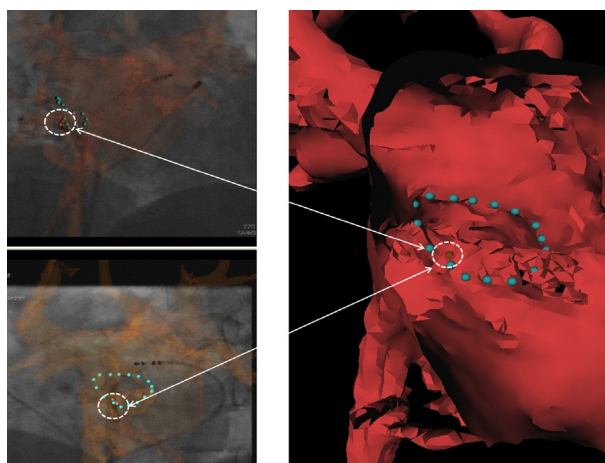
Fig. 4. Example of the integrated rendering of a patient specific model with live fluoroscopy views and the catheter tip tracked by Method 1. On the right side an endocardial view is offered in which the PV ostium target (ring of spheres) and the ablation catheter tip (encircled) are shown.

4 Conclusion & Discussion

We presented a method to track a catheter ablation tip from fluoroscopy images for the purpose of supporting atrial fibrillation treatment by catheter ablation. The method enables integration of a patient-specific model with the catheter tip in 3-D. It can provide an image-based alternative to commercial catheter tracking systems that have an important associated cost.

We realized a new catheter tracking approach by combining a template based registration with a limited set of templates and a Kalman filter for optimization

of the search problem in a robust and fast way and for smoothing the discretized orientation.

We could show that both proposed methods performed equally well and that the accuracy of 1.7 mm compares well to the reported accuracy of EM tracking systems (0.73 mm (Carto) & 4 mm (EnSite)). Because of the higher computational cost, we opt for Method 1 which was tested in a clinical situation. The tracking method performed well and the electro-physiologist found an endocardial visualization of the tip helpful in following the planned ablation trajectory around the PV.

Tracking was sometimes disturbed by other catheters but the method was capable of tracking the ablation tip correctly when the catheters moved away. Alternating fluoroscopy acquisition sometimes caused an error in the reconstruction of the catheter tip. Our future work will therefore focus on resolving these two limitations. This can, for instance, be accomplished by including a larger template that includes more proximal electrodes as well or by simultaneous acquisition of the fluoroscopic images. This, however, can only be justified if the amount of X-ray radiation can be kept equal or less than currently used.

The number of installed biplane systems is currently limited which restricts immediate clinical applicability. However, extension of the presented tracking approach for tracking multiple electrodes or an entire catheter could enable other applications in electro-physiology and beyond. This, in turn, could lead to a widespread cost-effective alternative to EM tracking systems.

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