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Automated 3D coronary sinus catheter detection using a scanning-beam digital x-ray system

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Abstract

Scanning-beam digital x-ray (SBDX) is an inverse geometry x-ray fluoroscopy system capable of tomosynthesis-based 3D tracking of catheter electrodes concurrent with fluoroscopic display. To facilitate respiratory motion-compensated 3D catheter tracking, an automated coronary sinus (CS) catheter detection algorithm for SBDX was developed. The technique uses the 3D localization capability of SBDX and prior knowledge of the catheter shape. Candidate groups of points representing the CS catheter are obtained from a 3D shape-constrained search. A cost function is then minimized over the groups to select the most probable CS catheter candidate. The algorithm was implemented in MATLAB and tested offline using recorded image sequences of a chest phantom containing a CS catheter, ablation catheter, and fiducial clutter. Fiducial placement was varied to create challenging detection scenarios. Table panning and elevation was used to simulate motion. The CS catheter detection method had 98.1% true positive rate and 100% true negative rate in 2755 frames of imaging. Average processing time was 12.7 ms/frame on a PC with a 3.4 GHz CPU and 8 GB memory. Motion compensation based on 3D CS catheter tracking was demonstrated in a moving chest phantom with a fixed CS catheter and an ablation catheter pulled along a fixed trajectory. The RMS error in the tracked ablation catheter trajectory was 1.41 mm, versus 10.35 mm without motion compensation. A computationally efficient method of automated 3D CS catheter detection has been developed to assist with motion-compensated 3D catheter tracking and registration of 3D cardiac models to tracked catheters.

Keywords

X-ray fluoroscopy; inverse geometry; scanning-beam digital x-ray; catheter tracking; coronary sinus

1. INTRODUCTION

X-ray fluoroscopy provides the high temporal and spatial resolution needed to visualize catheter-based interventional devices, however it lacks depth resolution and strong soft tissue contrast. In anatomically-targeted cardiac procedures such as catheter ablation of atrial fibrillation, the catheter device must be navigated in relatively large 3D cardiac chambers. Precise catheter positioning based on fluoroscopy alone can be challenging. Pre-acquired anatomic imaging (e.g. cardiac CT) may be projected and registered with live fluoroscopy to aid in the visualization of the ablation catheter relative to the targeted soft tissue anatomy,¹

although the display remains two dimensional. The scanning-beam digital x-ray (SBDX) system is a fluoroscopic system (see Fig. 1) that can perform 3D catheter tracking simultaneous with fluoroscopy using real-time tomosynthesis.² This technology could potentially provide a live 3D display of catheter position registered to a pre-acquired 3D model of cardiac anatomy.

A display combining live device imaging with a pre-acquired model of cardiac anatomy requires a motion-compensated model registration method. The coronary sinus (CS) is located next to the pulmonary veins (PV), and thus any movement of a CS catheter closely reflects movement of the anatomic target in ablation procedures (e.g the PV antrum).³ Motion compensation based on the CS catheter position has been used to improve model registration accuracy in 2D displays.⁴ Although the major respiratory-induced motion of the heart is in the inferior-superior direction, there are motion components in all three dimensions.^{5,6} This three dimensional motion must be measured to provide accurate 3D motion compensation in a 3D display based on SBDX imaging.

The purpose of this work was to develop an automated, computationally efficient method of 3D CS catheter detection for SBDX. The algorithm is intended for use in a motion-compensated 3D display of SBDX catheter tracking. Specifically, it is designed to allow an imported model of cardiac anatomy to remain registered to a tracked CS catheter, while other catheters (e.g. an ablation catheter tip) are freely tracked and displayed relative to the anatomic model (see Fig. 2). In this method, SBDX real-time tomosynthesis is applied to localize individual catheter electrodes in 3D. Then a novel 3D extension of a technique developed by Ma *et al.*⁷ for 2D images is used to detect and group the elements of the CS catheter. Phantom studies were used to characterize CS catheter detection and motion compensation under different imaging conditions.

2. METHODS

2.1 SBDX 3D catheter localization

SBDX is an inverse geometry fluoroscopic system designed for cardiac interventions (Fig. 1).⁸ The x-ray tube generates a rapidly scanning narrow x-ray beam by deflecting an electron beam over a transmission-style tungsten target in a raster pattern. Typically, an array of 71×71 focal spot positions is scanned in each 1/15 s frame. Each focal spot is collimated to a 5.3 cm tall $\times$ 10.6 cm wide (160×320 elements) photon counting detector with a 2 mm thick CdTe x-ray converter. This imaging geometry is a form of real-time tomosynthesis. To form the live fluoroscopic display, first 32 planes spaced by 5 mm along the source-detector axis are reconstructed via shift-and-add digital tomosynthesis. Then a composite image displaying the sharp, in-plane features is generated using a pixel-by-pixel plane selection algorithm (Fig. 1D).

It has been shown that the blurring behavior in the intermediate tomosynthesis plane stack may be analyzed to achieve frame-by-frame 3D localization of discrete metallic catheter elements with approximately 1 mm accuracy.² The localization algorithm has three basic steps: 1) spatial filtering is applied to each plane emphasize high contrast, in-focus features, 2) a maximum intensity projection (MIP) of the filtered images is segmented to identify

distinct objects in the field-of-view, and 3) each object is localized along the source-detector direction by calculating the center-of-mass (COM) of sharpness versus plane position. Details of the catheter tracking algorithm can be found in Ref. 2. This algorithm has recently been implemented in real-time at 15 frame/s.⁹

2.2 3D coronary sinus catheter detection

A CS catheter can be modeled as a smooth, curvilinear structure with electrodes spaced at regular intervals (Fig. 2). A photograph of a CS catheter is shown in Fig. 2(A), and a composite image with an ablation catheter, CS catheter, and fiducials in an anatomic phantom is displayed in Fig. 2(B). A real-time, 3D SBDX catheter tracking display of the localized ablation catheter tip and the electrodes of the CS catheter is shown in Fig 2(C), along with a preacquired 3D model of an atrium phantom. Ma *et al.* have shown that this prior knowledge of the CS catheter geometry can be combined with an object detection technique to achieve real-time automated CS catheter recognition in 2D images.⁷ They use a fast blob detector based on the determinant of the Hessian matrix to detect electrodes. The method assigns a score value for each detected blob. The algorithm then selects the 10 blobs with the highest score as potential tip electrodes. For each potential tip, the algorithm then performs shape-constrained searching to select eligible points within 5 mm and with a bending angle of less than 90° to the preceding point. The search continues until the expected number of catheter elements is found or no additional points satisfy the search criteria. A weighted cost function is then used to determine which of the ten groups is most likely the CS catheter using terms including: blob size, variation in bending angle, ratios of chord and curve lengths, and the expected number of electrodes.

This method was modified and applied to the 3D results of SBDX catheter tracking. The method begins by identifying potential CS catheter candidates based on 3D geometry (Alg. 1). Potential catheter candidates are identified by testing all permutations of three localized objects for the possibility of belonging to the CS catheter, using 3D distances and angular limits between neighboring points to reject unlikely candidates (Fig. 3(A–C)).

Algorithm 1

Coronary sinus catheter initialization

```

1:  For frame:  $f$ 
2:    Acquire full field-of-view images
3:    Localize objects
4:    For each permutation of 3 objects:  $[A, B, C] = P(NumObj, 3)$ 
5:      If  $\overline{AB} < D_{max} \&\& \overline{BC} < D_{max} \&\& \theta_{ABC} < \alpha_{max}$ 
6:        Select pointset as a potential catheter candidate
7:        Add distance and angle to catheter total
8:      End if
9:    End for
10:  End for
```

Figure 3(A) shows a point being rejected by having a distance, D , greater than the threshold distance, $D_{\max}$. Figure 3(B) demonstrates that points with a bending angle of α greater than the threshold $\alpha_{\max}$ are rejected. Three points are selected for initialization as this is the smallest grouping that provides both distance and bending angle information. The maximum and minimum allowable distances are based on physical measurements of the CS catheter. The maximum bending angle between neighboring electrodes (30°) was empirically chosen to avoid sharp bends which are unlikely when a CS catheter is placed within the coronary sinus.

For each surviving 3-point candidate, a modified 3D extension of Ma *et. al.*'s shape-constrained CS catheter search algorithm (Alg. 2) was performed to link additional points to the group. The additional linkage of points is necessary as CS catheters typically have 5–10 electrodes depending on the specific design, and each electrode is independently trackable. Because the potential catheter candidates begin with 3 selected points, any additional remaining points meeting the search criteria are added to the potential catheter.

Algorithm 2

Shape constrained search

```

1:   Begin with the 3 points from successful initialization
2:   For each remaining point,  $P$  where  $P \in$  unselected points
3:       Find point  $P$  closest to preceding point
4:       If  $\overline{CP} < D_{\max}$ 
5:           If  $\theta_{BCP} < \alpha_{\max}$ 
6:               If measured catheter length < known catheter length
7:                   If measured catheter bend < estimated coronary sinus bend
8:                       Add the point to CS catheter
9:                       Add distance and angle to catheter total
10:                  End if
11:              End if
12:          End if
13:      End if
14:  End for

```

The algorithm searches a conical region extending from the end point of the set of three points. The limited search area, which enforces a smooth catheter shape, is shown in Fig. 3(D). If multiple points fall within the conical search region, the point nearest to the apex of the cone is used. Points are added to the catheter candidate until either no additional points satisfy the search criteria ($\alpha < \alpha_{\max}$ and $D < D_{\max}$) or the total known catheter length or number of fiducials are reached. The result of this step is an additional group of 3D points that could represent the CS catheter. Each group will have its own calculated 3D length, cumulative bending angle, and 3D COM. A catheter-identifying cost function then selects the group that is most likely to be the CS catheter. The cost function (Eq. 1) determines the set of points that minimizes: 1) the differences in total detected catheter length compared with the known catheter length, 2) the difference between cumulative bending angle and the

expected angle for the coronary sinus vessel (55°), and 3) the distance from the previous frame's COM vector to the current frame's COM vector. The third term of the cost function enforces smooth catheter motion from frame-to-frame. This operates on the assumption that imaging and tracking at 15 fps produces relatively small intraframe differences in the catheter position. Cardiac motion of the left atrium is relatively small compared to the respiratory motion and can be mitigated with cardiac gating.^{5,10} The CS catheter is typically placed within the CS vessel and left alone during the procedure, therefore the motion of the CS catheter is expected to be primarily due to respiratory motion.

$$Catheter\ Cost = w_1 * |Length_{ref} - Length_{CS}| + \dots w_2 * |Angle_{ref} - Angle_{CS}| + \dots w_3 * |COM_{frame} - COM_{frame-1}|_2$$

(1)

In this work, the adjustable weights w_i were set to: $w_1=4$, $w_2=3$, $w_3=10$. The weights were determined empirically to produce the most accurate results for series 5, as defined in Sec. 2.3. The same parameters were then applied to all series. A pseudocode outline of the entire algorithm can be found in Alg. 3.

Algorithm 3

CS catheter detection

```

1:  While imaging
2:    For each frame
3:      Localize object positions
4:      If previous frame has a detected catheter
5:        Perform Coronary sinus catheter initialization
6:        For each initialized catheter
7:          Perform Shape constrained search
8:        End for
9:      End if
10:     Evaluate each potential catheter using the cost function
11:     Select the most likely catheter
12:   End for
13: End while

```

2.3 Phantom study

SBDX imaging was performed using a cardiac chamber phantom placed within an anthropomorphic chest phantom. The phantom contained a decapolar (10 element) CS catheter positioned within the coronary sinus, a four-electrode ablation catheter, and nine 2.33 mm steel fiducials which were added to provide “catheter clutter” not belonging to either the CS catheter or ablation catheter. Three-dimensional motion was created by panning and elevating the table. The panning was such that the CS catheter left and re-

entered the field-of-view during an image sequence. Each frame contained 5 to 24 discrete high contrast elements which were individually localized with the SBDX catheter tracking algorithm. An example image is shown in Fig. 4.

Image sequences were acquired under five different conditions (Table 1). In the first two sequences, the tunable SBDX tracking parameters were adjusted to achieve two forms of localization. In sequence 1, neighboring pairs of CS elements were localized as a single object. In sequence 2, the elements were individually localized. Sequences 3–5 tracked the CS elements in pairs, as in sequence 1, however fiducial clutter was also added to create challenging situations where the CS detection algorithm could potentially fail if the 3rd dimension (position along source-detector axis) had not been considered during tracking. The fiducials resembled CS catheter electrodes in the 2D image display, however they were separated from the CS catheter along the source-detector axis by different amounts ranging from –25.8 mm to +22.6 mm.

The performance of the CS catheter detection algorithm was characterized by counting the number of true positive (TP), true negative (TN), false positive (FP) and false negative (FN) results for a given experimental condition. True positive was defined as detection of all CS catheter elements in their correct positions, when the CS catheter was present. True negative was defined as not detecting the CS catheter when the CS catheter was not present. False positive was defined as detecting a CS catheter when it was not actually present. False negative was defined as not detecting any part of a CS catheter when the CS catheter was present, or detecting a CS catheter configuration that did not match all points of the true CS catheter configuration. True positive rate (TPR) was calculated as TP/P , where P is the total number of frames where the CS catheter was present. True negative rate (TNR) was calculated as TN/N , where N is the total number of frames with the CS catheter absent. The CS catheter detection algorithm was presented with raw 3D tracking results consisting of roughly equal parts of catheter-present and catheter-not-present cases.

Image sequences were also evaluated for the average processing time per frame and the number of times the detection algorithm automatically recovered after the CS catheter left and re-entered the FOV. Recovery of CS catheter detection is possible due to the global search of potential CS catheter candidates in each frame. The algorithm was implemented in MATLAB on a workstation equipped with an I5-4460 3.4 GHz CPU and 8 GB memory. The time to process the coordinates for each frame was measured using MATLAB's built-in profiler.

2.4 Motion compensation

A demonstration of motion compensation based on CS catheter detection and tracking was performed by imaging the phantom setup described in Sec. 2.3 while the table was manually panned and elevated. Simultaneously, an ablation catheter was pulled through a sheath affixed in the chest phantom at 10 mm/s using a linear motion stage. The table motion was used to generate motion of the CS catheter approximating respiratory motion. The range of table motion was 20 mm in the inferior-superior direction and 22 mm in the anterior-posterior direction. The ablation catheter tip, CS catheter electrodes, and other “clutter fiducials” were tracked using the SBDX 3D tracking algorithm. Table motion was recovered

from tracking results using the COM of the identified CS electrodes and the catheter trajectory.

To apply the motion compensation, the CS catheter was automatically detected and registered to the position and orientation of the CS catheter found in the first frame. Rigid iterative closest point (ICP) registration was used to determine a rigid 3D-to-3D transformation for each frame. This 3D-3D transformation was then applied to all other tracked objects (e.g. ablation catheter) in the image frame. In total 213 frames were processed.

The performance of the CS-catheter-based motion compensation was evaluated by comparing the 3D trajectory of the tracked ablation catheter tip to the known 3D trajectory as defined by its confining sheath. The root-mean-square distance (RMSD), mean distance, and standard deviation of the distance to the sheath centerline was evaluated with and without motion compensation. Given the 3D distance d_i from tip-to-centerline in the i^{th} frame and N frames,

$$RMSD = \sqrt{\frac{1}{N} \sum_{i=1}^N \|d_i^{tip-to-centerline}\|^2} \quad (2)$$

Performance metrics were calculated with and without motion compensation applied.

3. RESULTS

Detection results are broken down by image sequence in Table 2. Catheter detection performance was evaluated in a total of 2755 frames. The mean post-phantom fluence referenced to the isocenter plane was 11,420 photons/mm²/frame. True positive rate for all frames was 98.1% and ranged from 96.4% to 99.6% for individual sequences. True negative rate was 100% for all sequences, indicating that an ablation catheter and a moderate amount of clutter was not enough to cause false CS catheter detections. The global search of all points as a possible CS catheter allowed the detection algorithm to recover from situations where the catheter left and re-entered the field-of-view. The average processing time for all frames was 12.7 ms for the MATLAB implementation of the algorithm, corresponding to 78 frames per second for CS catheter detection.

The CS catheter was correctly identified in all 213 frames during the motion compensation experiment. Figure 5 shows the frame-to-frame motion vectors obtained from the COM of the detected CS catheter in the inferior-superior and anterior-posterior directions, with the green vectors corresponding to early frames and red vectors to late frames. Motion in the lateral direction was less than 1 mm and therefore excluded from the figure. These motion vectors correspond to the frame-to-frame table motion measured via CS catheter detection during the catheter pullback.

Without motion compensation, the tracked ablation catheter tip trajectory includes motion from the pullback through the sheath as well as the phantom as a whole (Fig. 6(A)). A

phantom-motion-compensated ablation catheter trajectory was generated as described in Sec. 2.4. After motion compensation was applied (Fig. 6(B)) the trajectory defined by the catheter sheath (Fig. 6(C)) was recovered.

The mean, standard deviation, and RMSD for the distance from the localized ablation catheter tip to the sheath centerline with and without motion compensation is listed in Table 3. Without motion compensation, the root mean squared deviation between the tracked ablation tip and the 3D centerline of the segmented sheath was 10.35 mm. Motion compensated ablation catheter tracking based on 3D CS catheter detection and 3D rigid registration reduced the RMSD to 1.41 mm.

4. DISCUSSION

Three-dimensional tracking of catheters based on real-time tomosynthesis is a unique feature of the SBDX system. This capability could be used to provide a novel 3D display of real-time ablation catheter position relative to a 3D model of the targeted patient anatomy. In such a display, it is desirable to provide motion compensation by registering the 3D anatomic model to the tracked 3D position of a coronary sinus catheter. This work reports a new, computationally efficient algorithm which achieves 3D CS catheter detection with high accuracy at rates necessary for real-time implementation. An advantage of this algorithm over existing 2D approaches is that the 3rd dimension along the source-detector axis can be used to distinguish between the CS catheter and clutter which would normally appear to be in close proximity with a 2D x-ray projection image.

An initial version of CS catheter detection and motion-compensation for the SBDX 3D catheter tracking display has been implemented in real-time at 15 frame/s. In this version, the CS catheter is continuously detected, and for each frame, a 3D-3D transformation is generated to map the tracked CS catheter position back to its position in the initial frame. During imaging the same 3D transformations are applied to all other tracked objects in the field-of-view. Therefore all tracked coordinates are effectively referenced to the CS catheter. Figure 7 shows a screenshot of this implementation, with the detected elements of the CS catheter connected by green lines, and a motion compensated ablation catheter tip (red arrow). Also shown is a 3D anatomic model of the left atrium and coronary sinus vessel, derived from a pre-acquired CT scan. Future work will examine performance of the algorithm in more realistic phantoms and animal studies.

5. CONCLUSIONS

The SBDX system provides live 3D catheter tracking based on real-time tomosynthesis. An accurate, automated algorithm for detection of a coronary sinus catheter has been developed to facilitate respiratory motion-compensated display of live 3D tracking data. In a phantom study, the method was robust to moderate amounts of clutter. The true positive rate of CS catheter detection was 98.1% and the true negative rate was 100%. The algorithm was found to be computationally efficient and has been implemented in the SBDX real-time catheter tracking pipeline.

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Fig. 1.

(A) SBDX system (B) Schematic of scanning source array, and a series of narrow overlapping beams directed at a small detector (C) Analysis of object blurring in tomosynthesis reconstructions is used for 3D catheter tracking. (D) Each live SBDX image frame is a composite of a stack of tomosynthesis images reconstructed in the frame period.

Fig. 2.

(A) 10-electrode coronary sinus catheter. (B) SBDX composite image of CS catheter and ablation catheter. (C) Real-time 3D display of SBDX-based catheter tracking, with a preacquired atrium phantom model (red). The yellow arrow identifies the CS catheter and the green arrow identifies the ablation catheter. The ablation catheter is placed inside a sheath which defines its trajectory during pullback experiments.

Fig. 3.

Search for CS catheter candidates. Blue spheres are localized points of the CS catheter, yellow represents points from other catheters or clutter. First, all possible combinations of 3 points are considered as candidates. Candidates are rejected if (A) point-to-point 3D distance exceeds the allowed distance, or (B) the angular bend that is larger than allowed. An acceptable candidate is shown in (C). A full CS catheter candidate is then constructed by adding points to the initial 3-point candidate (D). This involves a search within a 3D cone extending from the most recently added point.

Fig 4.
Image frame from sequence 5, showing the ablation catheter (yellow), coronary sinus catheter (blue), and 4 fiducials (red) added as clutter.

Fig 5.

Velocity vectors of the center-of-mass for the detector coronary sinus catheter. Green arrows are associated with earlier frames and red arrows with later frames.

Fig 6.

(A) Localized ablation catheter tip positions without compensation for phantom motion. (B) Localized ablation catheter tip positions after motion compensation. (C) Segmented catheter sheath which constrained the trajectory of the ablation catheter tip.

Fig. 7. Visualization from real-time catheter tracking implementation showing a segmented left atrium and coronary sinus vessel (red), tracked fiducials and catheter electrodes (gray spheres), and detected CS catheter (green connected spheres).

Table 1

Descriptions of the 5 image sequences analyzed.

Sequence number	CS catheter tracking method	Fiducial clutter positions
1	1 (Pairs tracked together)	-
2	2 (Pairs tracked individually)	-
3	1	22.6 mm anterior to CS
4	1	25.8 mm posterior to CS
5	1	Same plane as CS catheter

Table 2

Results of CS catheter detection algorithm.

Image Sequence	1	2	3	4	5	Total
Total Frames	401	858	443	596	457	2755
Frames w/catheter present (P)	138	344	173	264	243	1162
Frames w/o catheter present (N)	263	514	270	332	214	1593
True positive (TP)	133	338	169	258	242	1140
True negative (TN)	263	514	270	332	214	1593
False positive (FP)	0	0	0	0	0	0
False negative (FN)	5	6	4	6	1	22
True Positive Rate (TPR = TP/P)	0.964	0.983	0.977	0.977	0.996	0.981
True Negative Rate (TNR = TN/N)	1.000	1.000	1.000	1.000	1.000	1.000
Times recovered from leaving FOV	0/0	5/5	2/2	2/2	1/1	10/10
Mean processing time per frame [ms]	9.4	6.8	17.1	14.7	15.4	12.7

Table 3

Ablation catheter pullback tip to centerline distances.

	Motion compensation	Without motion compensation
Mean Distance [mm]	1.27	8.24
Distance Std. [mm]	0.62	6.29
RMSD [mm]	1.41	10.35