Semi-Automatic Basket Catheter Reconstruction from Two X-Ray Views

Xia Zhong[1], Matthias Hoffmann[1], Norbert Strobel[3], Andreas Maier[1,2]

[1] Pattern Recognition Lab, Department of Computer Science, Friedrich-Alexander University Erlangen-Nuremberg , Germany
[2] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander University Erlangen-Nuremberg, Germany
[3] Navigation Concepts, AT Innovation, Siemens Healthcare GmbH, Germany

Introduction

Multi-electrode Basket Catheter (Figure 1)

- Multi-electrode catheter to record 64 ECG signals
- Used for localizing the position of electrical anomalies during atrial fibrillation treatment [1]

Methods

- **Basket Catheter Spline Model**
  each catheter spline described using a active shape model [2]

$$\boldsymbol{p}_i = (\boldsymbol{p}_{i1}, \ldots, \boldsymbol{p}_{ik}, \ldots, \boldsymbol{p}_{i10})^T$$

$$\boldsymbol{x}_{ki} = \boldsymbol{R}_i^Y \boldsymbol{R}_i (\boldsymbol{p}_{ik} + \boldsymbol{t}_i) \qquad \hat{\boldsymbol{x}} = \bar{\boldsymbol{x}} + \boldsymbol{V}\boldsymbol{b}$$

$\boldsymbol{p}_{k,j} \in \mathbb{R}^3$: coordinate of k[th] electrode on i[th] spline
$\boldsymbol{R}_i^Y$,$\boldsymbol{R}_i$ and $\boldsymbol{t}_i$: rotation and translation for alignment
$\bar{\boldsymbol{x}}$: mean shape; $\boldsymbol{V}$: modes of variation; $\boldsymbol{b}$: weight factors

- **Electrode and Spline Detection**
  - detect electrodes using determinant of Hessian matrix
  - detect splines using a vesselness filter [3]
- **Point Cloud Generation by Triangulation**
  Correspondence: distance to epipolar line $< M_A$
  Motion Compensation: $\boldsymbol{P}_{\mathrm{A}}' = \boldsymbol{P}_{\mathrm{A}} \boldsymbol{T} \left(\boldsymbol{1} | (t_x, t_y, t_z)^T\right)$
- **Model Initialization and Adaption**
  - Length Adaption
    Most probable model

$$\boldsymbol{b}_k = \operatorname*{argmin}_{\boldsymbol{b}'} \|\tilde{\boldsymbol{p}}_1 - \tilde{\boldsymbol{p}}_{10}\| - \|\hat{\boldsymbol{p}}_1(\boldsymbol{b}') - \hat{\boldsymbol{p}}_{10}(\boldsymbol{b}')\| - a_0 \cdot \mathcal{N}(\boldsymbol{b}'; \boldsymbol{0}, \boldsymbol{\Sigma})$$

Multiple length adaption

$$R = \{\boldsymbol{r} = c_1 \cdot \boldsymbol{e}_1 + c_2 \cdot \boldsymbol{e}_2 + c_3 \cdot \boldsymbol{e}_3\} \; c_1, c_2, c_3 \in \{0, 1.0, -1.0, 1.5, -1.5\}$$

  - Rotation Initialization

$$\mathcal{D}(\mathbf{b}, \boldsymbol{\alpha}) = a_1 \cdot \underbrace{\left(\sum_i \min_k d\left(\boldsymbol{e}_i^{\mathrm{A}}, \boldsymbol{S}_k^{\mathrm{A}}(\boldsymbol{b}_k, \alpha_k)\right) + \sum_i \min_k d\left(\boldsymbol{e}_i^{\mathrm{B}}, \boldsymbol{S}_k^{\mathrm{B}}(\boldsymbol{b}_k, \alpha_k)\right)\right)}_{\text{Distance of each detected electrode to projected splines of the model}}$$

$$a_2 \cdot \underbrace{\left(\sum_i \min_{j,k} d\left(\boldsymbol{e}_i^{\mathrm{A}}, \boldsymbol{p}_{k,j}^{\mathrm{A}}(\boldsymbol{b}_k, \alpha_k)\right) + \sum_i \min_{j,k} d\left(\boldsymbol{e}_i^{\mathrm{B}}, \boldsymbol{p}_{k,j}^{\mathrm{B}}(\boldsymbol{b}_k, \alpha_k)\right)\right)}_{\text{Distance of each detected electrode to projected electrodes of the model}}$$

$$a_3 \cdot \underbrace{\left(\sum_{k,j} \min_i d\left(\boldsymbol{e}_i^{\mathrm{A}}, \boldsymbol{p}_{k,j}^{\mathrm{A}}(\boldsymbol{b}_k, \alpha_k)\right) + \sum_{k,j} \min_i d\left(\boldsymbol{e}_i^{\mathrm{B}}, \boldsymbol{p}_{k,j}^{\mathrm{B}}(\boldsymbol{b}_k, \alpha_k)\right)\right)}_{\text{Distance of each projected electrode of the model to detected electrodes}}$$

$$\boldsymbol{\alpha} = \operatorname*{argmin}_{\alpha_1, \ldots, \alpha_8} \mathcal{D}(\mathbf{b}, \alpha_1, \ldots, \alpha_8)$$

  - Image-based Model Adaption

$$\mathcal{R}(\boldsymbol{b}, \boldsymbol{\alpha}) = \; a_4 \cdot \underbrace{\sum_k \mathcal{N}(\boldsymbol{b}_k; \boldsymbol{0}, \boldsymbol{\Sigma})}_{\text{Model likelihood}} + a_5 \cdot \underbrace{\sum_k \boldsymbol{I}_{\mathrm{ds}}^{\mathrm{A}}(\boldsymbol{S}_k^{\mathrm{A}}(\boldsymbol{b}_k, \alpha_k)) + \boldsymbol{I}_{\mathrm{ds}}^{\mathrm{B}}(\boldsymbol{S}_k^{\mathrm{B}}(\boldsymbol{b}_k, \alpha_k))}_{\text{Distance of projected splines to detected 2-D splines}}$$

$$\boldsymbol{b}, \boldsymbol{\alpha} = \operatorname*{argmin}_{\boldsymbol{b}, \boldsymbol{\alpha}} \mathcal{D}(\boldsymbol{b}, \boldsymbol{\alpha}) + \mathcal{R}(\boldsymbol{b}, \boldsymbol{\alpha})$$

Evaluation

- **C-arm CT Data Set**
  18 3-D volumes of basket catheters with different deformations
- **Laboratory Bi-plane X-Ray with Different Dose**
  Bi-plane basket catheters X-ray images acquired with different dose setting (signal to noise ratios)
- **Clinical Data**
  Two X-ray views of the basket catheter inside the right atrium

Contact
xia.zhong@fau.de

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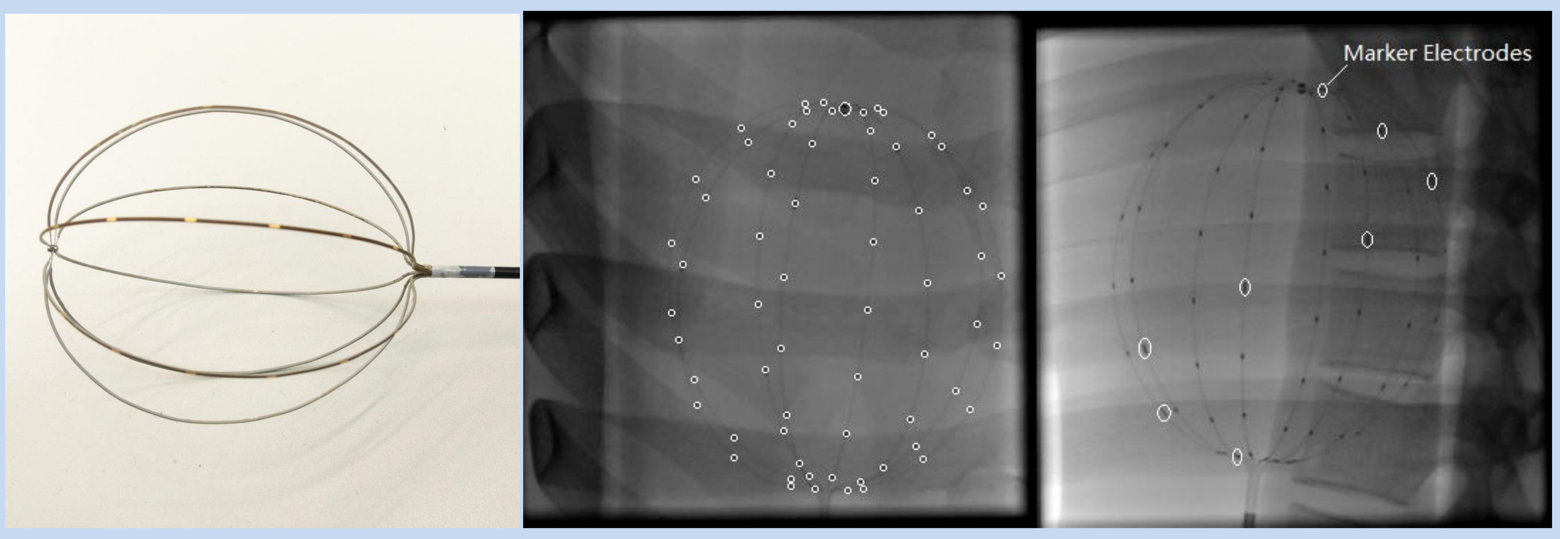

Figure 1: Basket catheter as seen in bi-plane images. The basket catheter comprises eight splines carrying eight electrodes. Each spline has a marker electrode.

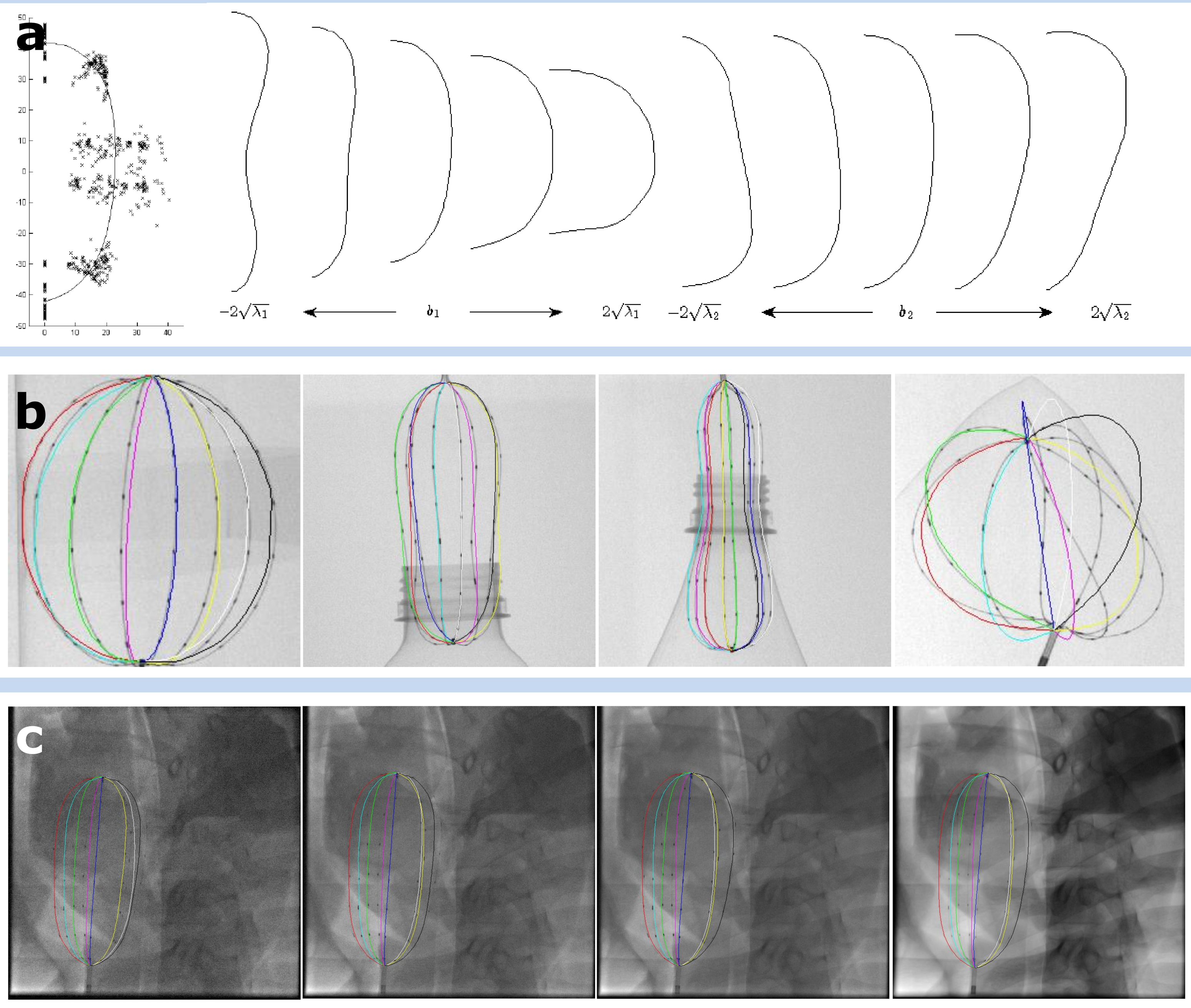

Figure 2: (a) The coordinates of a subset of the annotated electrodes, normalized and aligned with mean shape of the basket catheter spline model (left) and first two modes of variation. **(b)** X-ray images of basket catheter with different deformation in phantom and overlay of the reconstructed basket catheter. **(c)** X-ray images of basket catheter in phantom and overlay of the reconstructed basket catheter shown from left to right (increasing signal-to-noise ratio).

Reconstruction Error in mm				
	Single Marker		All Markers	
C-arm CT	2.2±2.2		2.0±2.0	
	Single Marker *(Figure 2c)*			
Lab Data	2.0±1.6	1.5±1.2	1.4±1.2	1.3±1.1
Clinical Data	4.6±3.5			

Discussion and Conclusions

- Result in phantom data is below the clinically relevant threshold of 3mm [4].
- In largely deformed and twisted real data, larger errors may occur.
- The median error in clinical data set was 3.4mm.
- The overlap of multiple catheters in clinical data introduces error.
- A robust catheter electrode detection is needed.

References

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