Estimation of a Vessel Side-Branches Model for Robotic Intravascular Navigation

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INTRODUCTION

Endovascular catheterization is a complex minimally invasive procedure which requires external imaging for intra-operative visual guidance. Fluoroscopy is the commonly chosen imaging modality. Yet, it is an X-ray based modality, limited to two-dimensional views of the imaged scene. Consequently, endovascular interventions still remain challenging and improved visual feedback would thus be advantageous [1]. Intra-operative modelling of blood vessels using local information from sensors embedded in the catheter has the potential to greatly improve surgical robots' or clinicians' awareness during navigation, while reducing the use of X-ray radiation [2].

In a previous work [3], a method for constructing a real-time intra-operative 3D approximation of the vessel geometry around a catheter tip was proposed. Intravascular Ultrasound (IVUS) imaging and Electromagnetic (EM) pose sensing were used together with an Unscented Kalman Filter (UKF) to estimate the best fitting local cylinder. The method showed good approximation capability of the vessel geometry, but in the absence of side branches. Nonetheless, the modelling of side branches is imperative as in some cases, the catheter must be steered into them to reach the desired target site. Additionally, they could serve as important navigation landmarks.

In this work, a new vessel model is proposed to allow estimating and representing side branches. In particular, as shown in Fig. 1, the side branches are modeled as holes in the local cylinder model that represents the main vessel (MV). Also, an UKF is implemented for inferring the parameters of the cylinder holes from synthetic IVUS and EM data. The proposed method is tested in a virtual vessel model making use of simulated IVUS and EM data.

MATERIALS AND METHODS

Two UKFs are used to: (1) locally approximate the MV by a cylinder around the catheter tip, as described in [3] and (2) approximate vessel side branches as holes in the aforementioned cylinder model.

Side-branches modelling: A side-branch is represented by a hole characterized by three variables with respect to the cylinder frame $\{cyl\}$, as shown in Fig. 2a: *i)* an angle $\alpha \in [0, 2\pi)$ in the xy plane of the cylinder perpendicular to its z-axis, *ii)* a displacement dz of the hole along the z-axis of the cylinder, and *iii)* a radius r. For each side branch j among the B detected side branches around the catheter tip ($j = 1, \cdots, B$), the hole parameters α_j, dz_j and r_j are added to the state vector to estimate, here defined as:

$$\mathbf{x}_k = \left[[\alpha_1 \quad dz_1 \quad r_1] \cdots [\alpha_B \quad dz_B \quad r_B] \right]^T. \qquad (1)$$

Side-branch detection: In the case at hand, synthetic IVUS data is directly generated as vessel contour points by intersecting the xy plane of the IVUS frame $\{i\}$ (see Fig. 1) with the simulated vessel. For each extracted contour, side-branch detection is carried out. A side branch is considered detected when *i)* the distance between the center of the side-branch ostium and its projection on the xy plane of $\{i\}$ is smaller than the side branch radius; and *ii)* the distance of the IVUS probe to the projected side branch ostium's center is smaller than a user-defined value (e.g. 20 mm) (see Fig. 2b). Note that in simulation, both the side-branch ostium center and the radius are known from the mesh geometry. After this step and the estimation

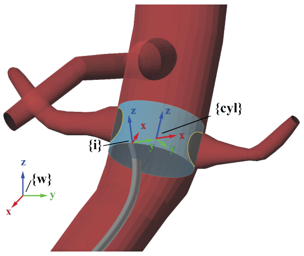
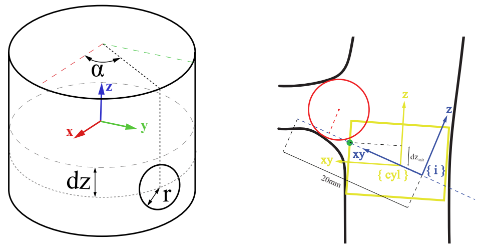


Fig. 1: Illustration of the MV model (light blue cylinder) and the side-branches models (holes in the cylinder, outlined in yellow). The proposed method is used to estimate the hole(s) state.



(a) (b)

Fig. 2: (a) Overview of the three variables that characterize a hole state in the MV cylinder model. α and dz determine the position of the side-branch hole in the cylinder, while r determines its radius. (b) Depiction of the side branch detection and initial dz-value calculation strategies. The red circle represents the side branch ostium characterized by a center location and a radius; the yellow rectangle represents the MV cylinder model.

This work was supported by the ATLAS project. The ATLAS project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 813782.

of the local MV cylinder model, the hole(s) state estimation is performed. From the side branch detection strategy, the initial α-values are obtained by projecting the branch center point onto the xy-plane of $\{i\}$ and then determining, on the same plane, the angle between the origin of $\{i\}$ and the projected point. Similarly, the initial dz-values are calculated first, by finding the intersection point with the MV estimated cylinder and a line along α (defined in the xy-plane of $\{i\}$) and second, by taking the distance from the cylinder position (origin) to the intersection point projected onto the cylinder z (longitudinal) axis. A representation of how these initial values are determined is shown in Fig. 2b. Finally, considering that a side branch is stationary relative to the moving local cylinder modelling the MV, a side branch is deleted from the state vector whenever dz exceeds a given threshold. This threshold is computed based on the height of the cylinder model from the MV and it is an indication that the side branch is no longer close to the catheter tip.

Filtering for side-branches model estimation: In the UKF implementation hereby described, the hole(s) state is first predicted based on the transformation of the MV approximated cylinder between the current and the previous frames, and then updated by considering the contour points of the vessel lumen and side branches in the xy-plane of the IVUS probe. Both α and dz at time $k-1$ are expressed in the new frame $\{cyl\}_k$ by, respectively, considering the rotation and the translation of the cylinder around its z-axis between $k-1$ and k, as described in

$$\mathbf{x}_k = \mathbf{x}_{k-1} + \mathbf{u}(\mathbf{e},\mathbf{f},\mathbf{R},\mathbf{p}), \quad \text{where}$$

$$\mathbf{u} = \begin{bmatrix} -atan2\left(\left({}_{i_k}\mathbf{R}^{i_{k-1}}\ {}_{i_{k-1}}\mathbf{f}\right)_{i_k}\mathbf{e},\ \left({}_{i_k}\mathbf{R}^{i_{k-1}}\ {}_{i_{k-1}}\mathbf{e}\right)\ {}_{i_k}\mathbf{e}\right) \\ -\left({}_{w_k}\mathbf{p} - {}_{w_{k-1}}\mathbf{p}\right) \cdot {}_{w_{k-1}}\mathbf{d} \\ 0 \end{bmatrix}. \tag{2}$$

${}_{i_k}\mathbf{e}$ and ${}_{i_k}\mathbf{f}$ are unit vectors along the cylinder x and y axes, respectively, at time k expressed in the IVUS frame $\{i\}$; ${}_{i_k}\mathbf{R}^{i_{k-1}}$ is the rotation matrix of the IVUS frame $\{i\}$ between time $k-1$ and k; ${}_{w_k}\mathbf{p}$ is the cylinder position in the world frame $\{w\}$ at time k; and ${}_{w_{k-1}}\mathbf{d}$ is the direction of the cylinder in frame $\{w\}$ at time $k-1$.

In order to describe the observation function $\mathbf{h}(\mathbf{x}_k)$ output, the cylinder with holes is intersected with the xy-plane of $\{i\}$. First, the distances of the origin of $\{i\}$ to M evenly spaced (every $\frac{2\pi}{M-1}$ radians) intersection points ${}^k_i\tilde{\mathbf{c}}(k=1,\dots,M=10)$ of the xy-plane of $\{i\}$ with an infinite cylinder are determined. Second, the distances of the intersection points S within the side-branch section (subset of M) are adjusted by a user-defined factor of 1.3:

$$\mathbf{h}(\mathbf{x}_k)=\left[||{}^1_i\tilde{\mathbf{c}}||\cdots\left[1.3\cdot||{}^1_i\tilde{\mathbf{c}}||\cdots1.3\cdot||{}^S_i\tilde{\mathbf{c}}||\right]\cdots||{}^M_i\tilde{\mathbf{c}}||\right]^T \tag{3}$$

RESULTS

An experiment was carried out with a virtual catheter advancing inside a simulated aortic model with 4 side branches (see an example with 3 side branches in Fig. 1).

Experimental setup (simulation): The catheter was steered repeatedly by translating it 10 mm forward at 2 mm/s, followed by a series of bending motions at 5 °/s: *i)* 36° bending of the catheter in one plane, *ii)* 360° rotation of the bending plane and *iii)* -36° bending in the bending plane, returning to the original orientation. For more realistic conditions, zero mean Gaussian noise with a standard deviation of 0.3 mm and 0.5° was added to the translation and rotation components of the catheter EM data, respectively; and zero mean Gaussian noise with a standard deviation of 1 mm was added to the IVUS data. The IVUS probe, the EM sensor and the catheter tip were assumed to be aligned by construction. Also, Gaussian noise with zero mean and 5° standard deviation was added to the α-values obtained from side-branch detection.

TABLE I: UKF parameters for side-branches model estimation

$\mathbf{x}_0$	$[\alpha_{\text{detected}}\ \text{dz}_{\text{detected}}\ 4\,\text{mm}]$
$\mathbf{P}_{\mathbf{x}_0}$	$\text{diag}([\frac{\pi}{18}\ 5\,\text{mm}\ 0.1\,\text{mm}])^2$
$\mathbf{P}_{\mathbf{v}_k}$	$\text{diag}([\frac{\pi}{180}\ 0.5\,\text{mm}\ 0.1\,\text{mm}])^2$
$\mathbf{P}_{\mathbf{n}_k}$	$\text{diag}([4\,\text{mm}\ \dots\ 4\,\text{mm}])^2$
$[\kappa\ \alpha\ \beta]$	$[0\ 1\ 2]$

Hole estimation evaluation: The filter performance was evaluated by means of two error metrics, computed at each simulation step: *i)* the distance error of the approximated side-branch representation and the ground-truth side-branch model (hole), and *ii)* the difference between the estimated radius and the ground-truth radius. The errors progression for each side branch and the errors distribution for all branches, including the median and interquartile range values, are shown in Fig. 3.

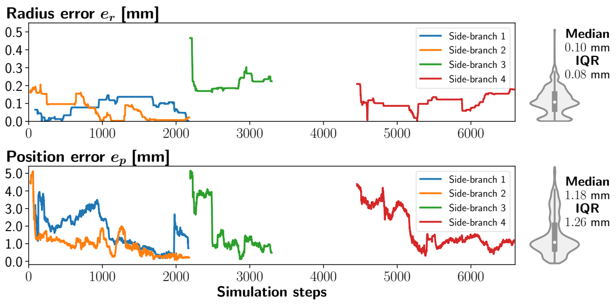


Fig. 3: Position and radius errors progression (left) and distribution (right) of the different side-branches models.

CONCLUSIONS AND DISCUSSION

The proposed method aims at determining reliable 3D vessels including side branches by expanding a prior cylinder model. From the low medians and IQRs shown in Fig. 3 (Radius: 0.10 mm and 0.08 mm; Position: 1.18 mm and 1.26 mm, respectively), the obtained results demonstrate the potential of using holes to model the ostium of side-branches. Future work is planned to compare the hole model with more detailed side-branch models and to conduct *in vitro* validation with real IVUS and EM data.

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