Fusing Intravascular Ultrasound and Electromagnetic Tracking Towards Non-Ionizing Intra-Operative Three-Dimensional Vessel Reconstruction

Beatriz Farola Barata[1,2], Montse Ainchil[1], Gianni Borghesan[1,3], and Emmanuel Vander Poorten[1]

[1]*Robot-Assisted Surgery Group, Department of Mechanical Engineering, KU Leuven, Leuven 3001, Belgium*
[2]*Altair Robotics Laboratory, Department of Computer Science, University of Verona, Verona 37134, Italy*
[3]*Flanders Make@KU Leuven, Leuven, Belgium*

INTRODUCTION

Endovascular interventions are complex minimally invasive procedures involving precise steering of percutaneously inserted catheters and guide-wires through the vasculature. Fluoroscopy is still the commonly chosen imaging modality for intra-operative visual guidance, despite the introduction of various image guidance approaches attempting to mitigate radiation exposure and facilitate 3D visual feedback. Fluoroscopy is an X-ray based modality, limited to two-dimensional views of the imaged scene. Better knowledge on the intra-operative 3D structure of blood vessels would thus be highly advantageous, potentially contributing to a decrease in the complexity of endovascular interventions [1].

The SCEM framework has been proposed to fuse Intravascular Ultrasound (IVUS) imaging and Electromagnetic (EM) pose sensing for intra-operative vessel reconstruction. Yet, this approach still relies on pre-operative data [2], [3]. A previous work [4] proposed to construct a real-time intra-operative 3D local approximation of the main vessel (MV) geometry around the catheter tip. IVUS imaging and EM pose sensing were used together with an Unscented Kalman Filter (UKF) to estimate the best fitting local cylinder. This information could be used to robustly steer the catheter tip towards the lumen's center.

In this work, an approach to reconstruct the entire 3D vessel based only on IVUS and EM sensing is introduced. The 3D local cylinder model from [4] is used as basic input to generate a local reconstruction. Global reconstruction is then achieved by merging multiple local reconstructed meshes. The proposed strategy is evaluated in a simulation environment with synthetic IVUS and EM data.

MATERIALS AND METHODS

The proposed 3D vessel reconstruction strategy iterates over three main phases, as illustrated in Fig. 1: *i)* defining a local primitive shape from the estimated 3D MV cylinder model, *ii)* mapping the primitive shape vertices to a point cloud of IVUS measurements around the cylinder model, and *iii)* merging the (mapped) local reconstructed mesh to the global mesh reconstructed from the previous iterations.

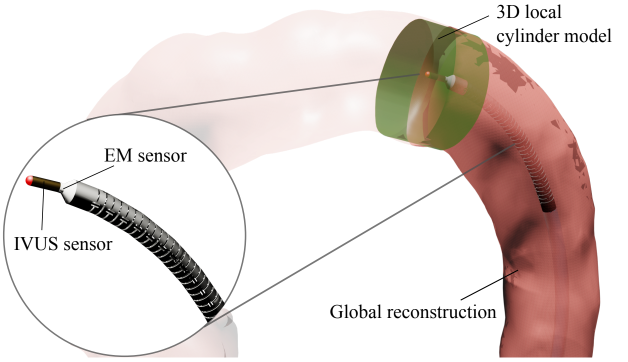

Fig. 1: Illustration of the main vessel cylinder model (green) and the reconstructed global mesh (dark red). The proposed method is based on a local primitive shape created from a 3D main vessel model estimated recursively and it only further depends on IVUS and EM data.

Local primitive shape: The primitive shape is created as a lateral surface mesh of the MV local cylinder with two triangular elements per cylinder slice sector. The user defines the number of sectors M and slices N per primitive cylinder shape. A slice sector is thus characterized by two variables: a radial angle $\theta = {}^{2\pi}/_{M}$ and a slice height $s = {}^{h}/_{N}$. The term h is the (fixed) height of the local cylinder model, as described in [4].

Primitive shape mapping: Once created, the local primitive shape is mapped to the IVUS measurements point cloud surrounding the lumen model, following 10 steps (Fig. 2):

1) generation of a 3D grid in the local coordinate frame $\{cyl\}$ of the cylinder model using θ as the radial discretization parameter and s for axial slicing;
2) transformation of the IVUS measurement point cloud to the current cylinder model frame $\{cyl\}$;
3) assignment of each IVUS measurement to the corresponding grid cell based on its cylindrical coordinates;
4) computation of the average Euclidean distances between each triangular element of the primitive shape and the relevant IVUS points: the fitting distances;
5) removal of IVUS measurement outliers if their fitting distances are not within the distribution minimum and maximum;
6) re-computation of the average fitting distances per triangular element;
7) setting the travel distance of triangular elements with

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.

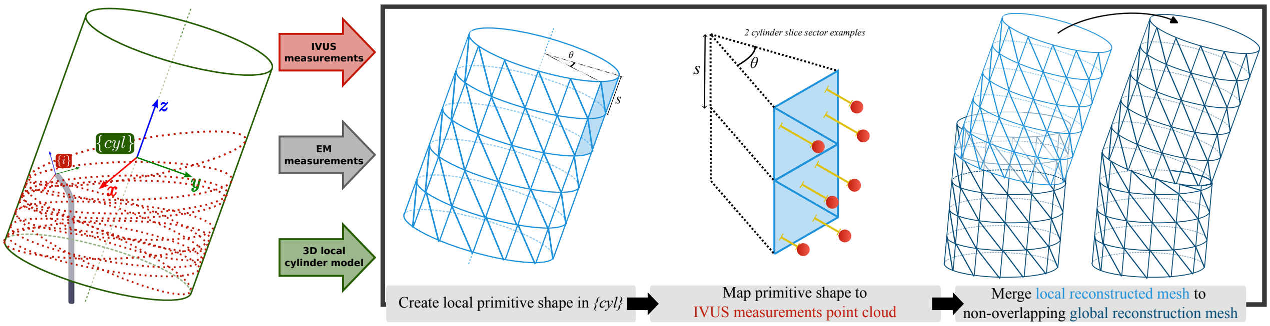

Fig. 2: Workflow of the proposed local-to-global 3D vessel reconstruction strategy (inside black box) with only IVUS contours (in red), EM poses and 3D local cylinders (in green) as inputs. Local and global reconstruction illustrations are shown in light blue and dark blue, respectively. Note that, for simplicity, reconstruction results are depicted as cylinders.

no associated IVUS points as the average fitting distances of the adjacent triangles;

8) computation of primitive shape vertex displacements *d* by averaging the fitting distances of the adjacent triangles;
9) translation of each vertex of the local cylinder mesh by *d* along its radial direction;
10) repeat steps 3 to 8 until the mean distance between the IVUS point cloud and the morphed cylinder falls below a user-defined threshold or the number of iterations is higher than a pre-defined maximum value.

The output of the aforementioned sequence is the local MV reconstruction mesh L_N.

Global reconstruction: The global 3D lumen reconstruction mesh is recursively built up by merging the locally reconstructed cylinder mesh L_N with the (global mesh) result of the previous iterations G_{N-1}:

$$\mathrm{G}_N = (\mathrm{G}_{N-1} \cap \overline{\mathrm{L}_N}) \cup \mathrm{L}_N \tag{1}$$

where $(\mathrm{G}_{N-1} \cap \overline{\mathrm{L}_N})$ removes any overlapping slices of the past global and the current local reconstruction results.

EXPERIMENTS AND RESULTS

An experiment was carried out in a simulation environment in which a virtual catheter was advanced inside a patient-specific aortic model along its arch (Fig. 1). This model was derived from segmented CT scans of a patient's aorta (with a radius of approximately 16 mm).

During catheter navigation, synthetic IVUS and EM measurements were generated. 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. Similarly, 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. From these, a 3D cylinder model representing the local lumen geometry was recursively estimated [4]. The IVUS, EM and 3D cylinder model data were then used as the inputs of the proposed lumen reconstruction approach.

The algorithm performance was evaluated by computing the fitting errors between the reconstructed and ground-truth meshes at each simulation step. These errors correspond to the distance between the vertices of the reconstructed and the ground-truth vessel meshes. The errors distribution and the fitting errors colormap for the entire simulation length, including the median and interquartile range (IQR) values, are shown in Fig. 3. Overall, a median of 0.40 mm and an IQR of 0.11 mm were obtained. The processing time for one iteration was about 27 ms.

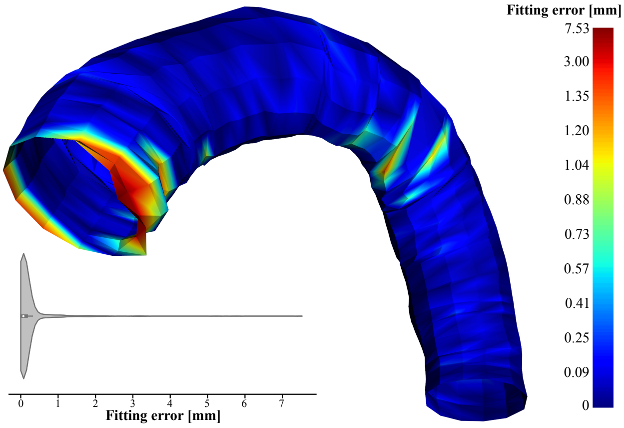

Fig. 3: Fitting errors (values in colorbars) representations and distributions of the patient-specific aortic model reconstruction.

DISCUSSION AND CONCLUSIONS

The proposed method aims at achieving reliable 3D vessel reconstruction from only IVUS and EM data. The obtained low median (0.40 mm) and IQR (0.11 mm) in Fig. 3 demonstrate the potential for achieving a zero-radiation global 3D lumen reconstruction which can be used for endovascular navigation and does not depend on a pre-operative geometry. Future work is planned to validate the proposed algorithm *in vitro* with real IVUS and EM data, and in more realistic clinical conditions to mimic physiological processes.

REFERENCES

[1] H. Rafii-Tari *et al.*, "Current and emerging robot-assisted endovascular catheterization technologies: A review," *Annals of Biomedical Engineering*, vol. 42, no. 4, pp. 697–715, 2014.

[2] E. Vander Poorten *et al.*, "Cognitive autonomous catheters operating in dynamic environments," *Journal of Medical Robotics Research*, vol. 1, no. 3, pp. 1–25, 2016.

[3] C. Shi *et al.*, "Three-dimensional intravascular reconstruction techniques based on intravascular ultrasound: A technical review," *IEEE Journal of Biomedical and Health Informatics*, vol. 22, pp. 806–817, 5 2018.

[4] B. Farola Barata *et al.*, "Ivus-based local vessel estimation for robotic intravascular navigation," *IEEE robotics and automation letters*, vol. 6, no. 4, pp. 8102–8109, 2021.