Endoscopic Optical Coherence Tomography Volumetric Scanning Method with Deep Frame Stream Stabilization

Guiqiu Liao[1,2,*], Oscar Caravaca Mora[1,*], Benoit Rosa[1], Diego D'Allaba[2], Alexandre Asch[1], Paolo Fiorini[2], Michel de Mathelin[1], Florent Nageotte[1], Michalina J. Gora[1]

[1] ICube Laboratory, University of Strasbourg,

[2] ALTAIR Robotics Laboratory, The University of Verona

** This authors contributed equally to this work*
guiqiu.liao@icube.unistra.fr;

INTRODUCTION

Optical coherence tomography (OCT) is increasingly used in biomedical and clinical imaging due to its combination of high-speed optical sectioning and high resolution. Side-viewing OCT probes with proximal scanning have been successfully used in the diagnosis of intravascular diseases, the itravascular stent strut assessment, as well as in the digestive tract. The rotational distortion of proximal-scanning endoscopic optical coherence tomography is significant due to the friction of optical fiber between the wire wall and the variable torque of the optical fiber. It can be further increased in the case of a steerable catheter used for large area scanning using a flexible robotized endoscope [1]. The robotized steerable OCT user can navigate the probe using telemanipulation with bending, translation and rotation of the steerable OCT catheter.

This work is focused on correction of image artifacts presented in three-dimensional OCT imaging in rotational scanning. The results show a significant reduction of the image precession when implementing a robotic pullback instead of the conventional internal pullback of the optical probe. In this case the whole OCT catheter is in motion during the 3D-scanning eliminating the torsion caused by the internal friction between the sheath and the rotating probe, so that the precession is 90% reduced in comparison with the conventional pullback scanning. In order to fully reduce remaining precession, which can be attributed to motor speed instability, an image processing technique based on deep learning is also integrated.

MATERIALS AND METHODS

In this work, a steerable OCT instrument with an outer diameter of 3.5 mm is used for volumetric imaging [1]. The steerable instrument is terminated with a 2 cm long transparent sheath to allow three-dimensional OCT imaging using a side-focusing optical probe with two external scanning actuators. The instrument is connected to an OCT imaging system built around the OCT Axsun engine, with a 1310 nm center wavelength swept source laser and 100 kHz A-line rate. The OCT steerable catheter is compatible with one of two instrument channels of a robotized flexible intervention endoscope [2]. The distal end of the robotized endoscope can be bent in 2 degrees of freedom, translated and rotated. The steerable OCT catheter can be translated, rotated and bent in one plane. In addition, the rotation and translation of the inner OCT probe can also be controlled by a servo system.

Conventional internal pullback scanning was effect-tuated to image a 20 mm long 3D printed rectangular tube target in VeroWhite material (Figure 1(E)). In the next step the same pullback was effectuated using a robot. To estimate stability of the image, ImageJ was used to manually measure the rotation of the 4 internal corners of the rectangular tube for each 1 mm of spacing with respect to the first frame.

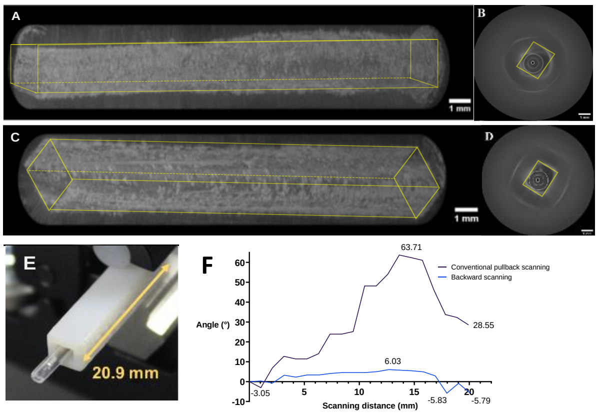

Figure. 1. Results of 3D reconstruction of the rectangular tube and the sum of the frames by performing regular pullback scanning (A, B)), and results of robotic pullback scanning (C, D). (E) Rectangular tube target for testing. (F) Angular rotation versus the pullback scanning distance (mm) for regular pullback and tool pullback with steerable catheter.

To further improve the alignment on the robotic volu-metric scanning data, a deep convolutional neural net-work (CNN) based video stabilization algorithm was applied to eliminate the image rotation distortion betw-een B-scans. This algorithm takes image sequence as input to get image correction vectors. To train the algo-rithm, a data set of 3.6 million image pairs is generated with 1800 true OCT images. Each image pair is generated by distorting original images with a random Non-uniform Rotational Distortion (NURD) warping vector. The training pipeline is implemented with Python codes, Pytorch framework is used for network implementation. After training the deep network for 14×10^4 iterations, it's deployed with a NVIDIA QT1000 graphics card to process the OCT data collected with the proposed scanning system. We calculated the standard deviation (STD) value and en-face projections [3] of videos to evaluated the efficiency of the stabilization algorithm.

RESULTS

A conventional OCT pullback scanning presented image rotation between 2D radial frames from -3.04° clockwise at 1.06 mm to a maximum rotation angle of 63.71° counterclockwise at 14 mm, ending in an angle of 28.55° at 20 mm (Fig. 1 F). When performing volumetric robotic scanning of the steerable OCT tool the image rotation was reduced to the range of 6.03° to -5.83° at 13 mm and 18 mm correspondingly. This constitutes an impr-ovement of approximately 90% in reduction of precession when preforming backward scanning. The actual scanning length was 20.9 mm and the speed of the pullback motion of the robotic instrument was 2.7 mm/s. Figure 1 shows the 3D reconstruction in both scanning methods. The conventional OCT pullback scanning presents major deformation in Figure 1(A) due to a large rotation angle, while such deformation is highly reduced in the case of robotic volumetric scanning in Figure 1(C). Figures 1(B, D) show the sum of all the frames to better demonstrate the difference of precession for each scanning method.

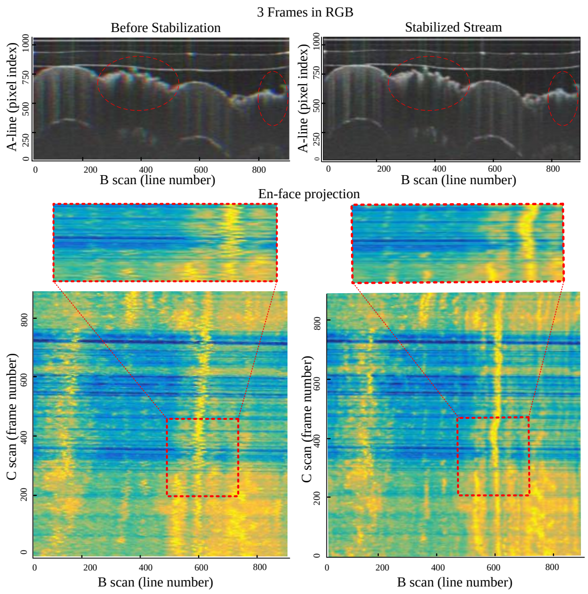

Figure. 3. Top row is the comparison of 3 adjacent frames in RGB channels, the bottom row is the comparison of A-line accumulated images with the videos containing 900 frames. The dashed circles mark out areas prohibiting significant NURD and corres-ponding stabilized result. The dashed boxes are enlarged for better visualization.

The STD value of the video before applying stabilization algorithm is 7.33 ± 0.52, which means it still experience fluctuation with a maximum value of 9.15. After applying the deep video stabilization algorithm to the data, the STD value of the video decreases to 6.19 ± 0.08, which has both lower mean value and variation.

In Figure 3, the top row shows 3 consecutive frames encoded in the red, green and blue (RGB) channels and superimposed to one individual image. The stabilization algorithm reduces the “colorful” part of unstable original frames significantly, while maintaining the texture characteristics of the original OCT images. It is also presented in en-face projections of the 3D OCT data set where each A-line is accumulated to one single value by mean intensity projecting (bottom row in Figure 3). In this case an X axis corresponds to a circumferential scanning and a Y axis to a longitudinal volumetric scanning. The frame size of one OCT image is 1024×832, which contains 832 A-lines. We transform 900 frames into a 900×832 matrix, and for display reason the matrix is normalized and the mean value is subtracted. Before stabilization, the image on the bottom left of figure 3 shows more unsmooth fluctuation. The right bottom image shows the A-line accumulation of stabilized robotic scanning data, which has less fluctuation, whereas its overall texture matches the overall texture of the bottom left image. This indicates that the algorithm can stabilize the video without changing other information in OCT images.

CONCLUSION AND DISCUSSION

We have demonstrated the potential benefit of implementing the pullback scanning with the robotic tool, our results show reduction of precession of the OCT images by about 90% in comparison with the regular internal pullback, significantly reducing as well distortion in 3D reconstruction.

With a deep learning based method applied to the robotic scanning data, the stabilization of OCT frame stream is further improved, representing by the reduced STD value and the lower fluctuation in the en-face projection. Other scanning methods using the automatic capabilities of the robot will be explored in the future work.

REFERENCES

[1] O. Caravaca Mora et al., “Steerable OCT catheter for real-time assistance during teleoperated endoscopic treatment of colorectal cancer,” Biomed. Opt. Express, Dec. 2019.

[2] A. De Donno et al., “Introducing STRAS: A new flexible robotic system for minimally invasive surgery,” Proc. - IEEE Int. Conf. Robot. Autom., 1213–1220 , 2013.

[3] Abouei, A. et al., “Correction of motion artifacts inendoscopic optical coherence tomography and auto fluorescence images based on azimuthal en face image registration,”Journal of BiomedicalOptics, vol. 23, no. 01, p. 1-14, 2018.

Acknowledgements

This work was supported by the ATIP-Avenir grant, the ARC Foundation for Cancer research, the University of Strasbourg IdEx, and funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 813782.