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Probabilistic Principal Component Analysis and Particle Filtering for real-time retina detection from a single-fiber OCT.

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***Abstract*—Vitreo-retinal surgery concerns a set of particularly demanding micro-surgical interventions that take place at the back of the eye. Examples of such procedures are retinal vein cannulation (where the surgeon aims to insert a needle in a vein of the size of human hairs) and epiretinal membrane peeling (where a detached membrane must be removed from the retina). As severe retinal damage can be caused by undesired collisions, good instrument to retina distance perception would be very useful. We propose to use an OCT-fiber instrumented tool, and purposefully designed algorithms to interpret the measurements and extract a reliable real-time distance estimate. This abstract describes the progress that was made and includes a test conducted with a robotic platform on a synthetic eye mockup.**

I. Introduction

Vitreo-retinal (VR) surgery is currently performed in a fully manual manner. Upon start of the procedure the surgeon carefully puts up to four trocars into place at 3 to $4\,\mathrm{mm}$ from the corneal limbus, the border between the cornea and the sclera Through these trocars thin instruments and illumination are inserted to operate on the interior part of the eye. The micro-surgeon observes the retina and relative instrument motion via a stereo-microscope positioned above the patient's eye. Depth perception is achieved by means of stereo vision, by observing the shadows that are cast by lateral illumination, by checking whether an instrument is in focus, or by indentation of the tissue (*e.g.* in the case of cannulation). These methods require significant expertise to be used effectively, given the small size of the structures the micro-surgeon is to deal with: for *epiretinal membrane peeling* (ERM-peeling) a membrane up to about $60\,\mu\mathrm{m}$ is to be peeled off; for ILM peeling the *internal limiting membrane* is only about $4\,\mu\mathrm{m}$ thick. Veins that are to be cannulated to treat *retinal vein occlusion* have diameters in the order of $100\,\mu\mathrm{m}$ - it is clear that inaccurate depth perception and depth control can cause serious complications [1], [2]. Research has been conducted to improve depth perception through adoption of alternative sensing techniques. OCT and force sensing are some of the more mature techniques that have been investigated in the past.

II. Goals and Related work

In this work we build further upon our earlier work [3] and on work of others such as [4] and [5], where OCT images have been employed in a number of algorithms targeting automatic segmentation of retinal layers, or to identify markers that predict certain diseases. Most of prior works rely on 2D or 3D OCT images, referred to as B- and C-scans respectively. Conversely, in [3], following the earlier work by Balicki *et al.*, [6], we employ OCT data that is acquired via an optical fibre incorporated directly inside the surgical instrument. This gives a one-dimensional depth scan also known as A-scan. Balicki *et al.* studied the use of A-scans with an OCT probe mounted on an micro-surgical pick; our work is mainly investigating its use for vein cannulation, more concretely we aim to the development of algorithms for robust distance estimation. Compared to [3], we evaluate and expand the earlier algorithm by introducing the use of a Particle Filter to overcome the problem of initialization that flaws Extended and Unscented Kalman Filters. In addition, we moved towards a more realistic setting by employing a robotic setup and the retina phantom shown in fig. 1, rather than relying on OCT B-scans captured through the microscope lenses, and interpret them as A-scans. We keep the retina modeling method that employs *probabilistic principal component analysis* (*PPCA*, [7]) to characterize a number of *latent* variables, as detailed in [3].

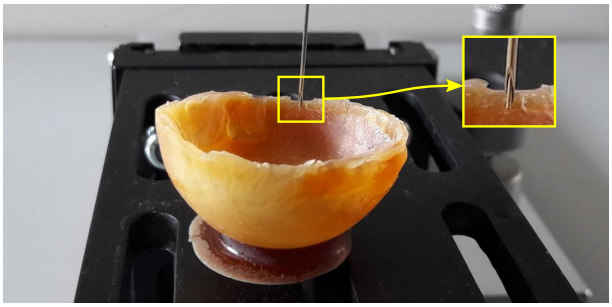

Fig. 1. Experimental setup showing the instrument (zoom in on fiber lens inside the needle) and the retina phantom (from *OptoMedical Technologies*)).

III. Materials

The setup is composed of: *i)* a 3DoF stage upon which *ii)* the OCT-Probe enabled instrument is mounted, *iii)* an OCT camera, *iv)* a synthetic eye mock-up. The instrument holds a fiber (assembled by *Medical Laser Center Lübeck GmbH*). The fiber is connected to an OCT camera by *OptoMedical Technologies GmbH* (OPM) which has been modified to be

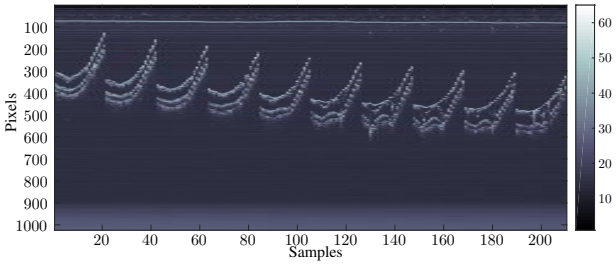

Fig. 2. Learning data set of 10 slices (0.4 mm spacing) of 21 points each (0.4 mm apart); the reflection of the fiber tip are visible at pixel ≈ 80.

used with the above mentioned fiber. The Eye mock-up, provided by OPM, a multi-layered phantom of human retina, including structures that resembles veins. A close up of the needle, fiber, and phantom is shown in fig. 1.

IV. Methods

The proposed procedure consists of a learning phase and a run-time identification phase (using a single line, as produced by an OCT fiber probe). Both phases are summarised next.

a) Learning phase: In order to build a base for the *PPCA*, we register scans in discrete points (each point is observed for 2 seconds, and an average is kept). Figure 2 shows the learning data set. *PPCA* needs a normalised training set (i.e. each pixel must represent the same information). To achieve this, we extract in a semi-automatic way some landmarks around important features. The data set is then re-sampled in such a way that these landmarks appear in the same area. *PPCA* defines the signal in function of the mean and modes. In such way, an approximated A-scan can be described in function of x:

$$x = [P \quad \Delta P \quad M1 \quad M2 \quad M3 \quad \ldots]$$

where P is the starting pixel where the mode is applied, ΔP is the number of pixels that is considered as window for the model, and Mi are the latent variables associated with the modes.

b) Tracking: Particle filtering is used to track the contour of the retina. Preliminary experiments have been carried out by scanning the synthetic eye with a movement parallel to the retina, building something analogous to a B-scan. Data is currently saved and processed offline with MATLAB (The MathWorks Inc.). A particle filter with state x and 200 particles is used. The first three modes are employed to reconstruct the measured signal. Figure 3 shows how the filter tackles a horizontal sweep, in which the fiber is moved of 8 mm in ≈ 8 s. In fig. 3 are reported: *i)* the time evolution of the estimated state (first 5 subplots), *ii)* the A-scans captured by the fiber superimposed with the time evolution of P (yellow), $P + \Delta P$ (green), and the estimated location of retina layers (red), and *iii)* the y position of the probe.

V. Conclusions

This abstract reported on the combination of local OCT sensing, retina modeling based on PPCA, and particle filtering. It was shown how this can be used to track in real-time the retinal layers with robot-assisted interventions in mind.

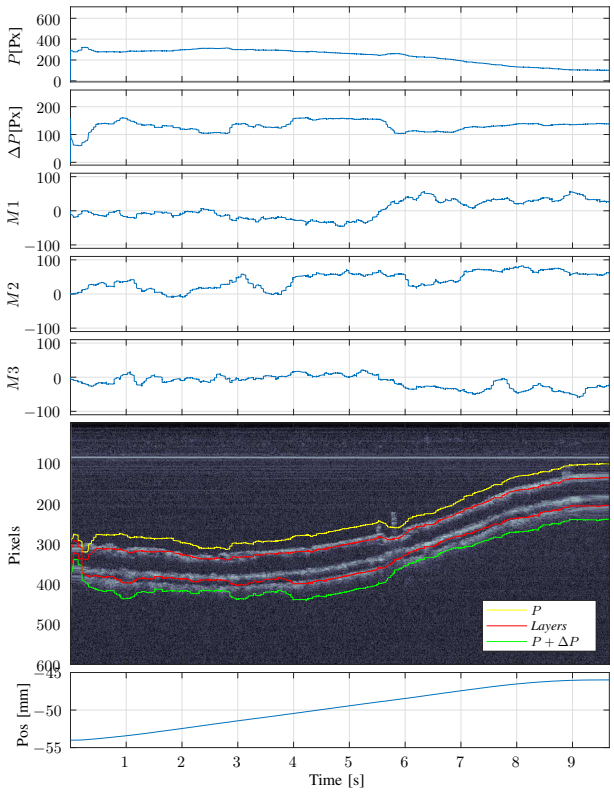

Fig. 3. Data from experiments; first five sub-plots show the time evolution of the estimated state, the sixth sub-plot shows the A-scan (Vs. time), and the layer estimation result, the last one the robot position. The constant peak around pixel 80 is the reflection of the lens at the tip of the instrument.

Acknowledgment

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