INTEGRATION OF REAL-TIME SIMULATIONS AND AUGMENTED REALITY FOR CATHETER MONITORING DURING PERCUTANEOUS PROCEDURES

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Introduction

Percutaneous approaches allow for minimally invasive treatment of structural heart diseases by implanting devices through a catheter that is inserted from a peripheral access into a blood vessel and driven to the intracardiac target structure. These approaches reduce convalescence time and surgery risks. However, these do not allow for direct vision of the catheter nor of the relevant anatomical structures, leading to the need for x-ray fluoroscopy to monitor the catheter. The use of x-ray fluoroscopy, and the associated risk for patients and operators, would be reduced if an alternative monitoring technology was available. To this aim, we propose the use of a sensorized catheter, the real-time simulation of its interaction with the relevant vessels as reconstructed from pre-operative imaging, and the rendering of real time results through mixed reality (MR) allowing for intuitive and ergonomic analysis of the model.

Methods

Catheter sensorization The distal tract of a catheter was equipped with fiber bragg grating (FBG) and electromagnetic (EM) sensors yielding the time-dependent (frequency=25 Hz) 3D position of 71 points homogeneously distributed (gap=8 mm) over the axis of the catheter [1].

Vessel model The 3D anatomy of the right femoral vein and the inferior vena cava of an adult male were reconstructed from CT scans. The anatomical model was embedded in a bounding box representing a linear elastic continuum (elastic modulus=1 MPa, Poisson ratio=0.3) mimicking the deformable constraint of the adjacent organs (Fig. 1).

Numerical simulation was developed in the open source *Sofa* framework [2]. Upon registration between the sensors reference frame (RF) and the vessel model RF, the virtual avatar of the catheter was defined as a series of 71 rigid spheres with 4 mm radius, equal to the cross-sectional radius of the catheter. These were displacement-driven based on the time-dependent data yielded by the sensors. To model catheter-vessel interaction, a collision model was implemented: the catheter was represented by a curvilinear cylinder fitting the 71 spheres. Contact between the cylinder lateral surface and the vessel wall was modeled by a Lagrangian Multiplier approach.

MR interface was implemented in Unity® and visualized through a Hololens™ 2 headset.

Dataflow from the sensors to computational model and to the MR interface was handled by ROS publisher/subscriber communication protocol, leveraging on ad hoc bindings and Unity® plugins.

Preliminary in vitro benchmarking was performed on a physical silicone replica of the vessel, included in a setup allowing for RF calibration and stereo-acquisition of markers on the wall of the vessel through high-speed cameras. The real sensorized catheter was inserted in the silicone phantom, and their physical interaction was simulated through the implemented modeling approach. The computed vessel wall displacements were compared vs. the 3D displacements of the real vessel wall reconstructed from stereo acquisitions.

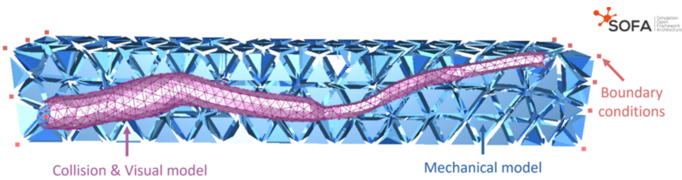

Figure 1: Vessel model and bounding box.

Results

20 test simulations were run on a state-of-the-art laptop. All converged and were stable; their real-time performance depended on the number of contact interactions, resulting in an update frequency of the MR rendering ranging from 25 FPS to 7 FPS. In the in vitro benchmarking, vessel wall displacement was computed with an average error of 1 mm.

Conclusions

The proposed framework consists in a simulation that computes the deformed configuration of the vessel by updating in real-time the shape and position of the catheter as provided by the sensors. The 3D data are streamed to Hololens™ 2 which allows the holographic display. The frame rate is not high enough to define the simulation interactive so further efforts are required to optimize the computation of the contact response. Future studies will be focused on the GPU implementation of the strategies adopted in this work and on the validation in an experimental set-up.

References

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2. Y. Payan. Springer, 2012. ISBN 9783642290138.

Acknowledgements

This work is part of the ARTERY project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017140.