Towards Intraoperative Use of Surgical Simulators: Evaluation of Catheter Insertion Models

G. Smoljkic, C. Gruijthuijsen, J. Vander Sloten and E. Vander Poorten

***Abstract*—Accurate and precise control of a catheter's position inside the vasculature remains a difficult and important task. Current manual approaches rely very much on the surgeon's expertise as visual information is extremely limited. The intraoperative use of fluoroscopy for real-time visualization of the catheter and the vasculature leads to safety issues, both for the patient and for the surgeon. By introducing robotically steered catheters these disadvantages can be at least partially alleviated. Also, robotics could improve the repeatability and accuracy of the catheter motion inside the vasculature. Due to the complexity of the catheter-vessel interaction current robotic steering relies completely on the surgeon's skills and experience. Based on the own experience and fluorscopic imaging surgeons form themselves mental maps of the catheter-vessel system. Within these maps the robot's joints are commanded one at a time. In order to introduce more sophisticated and coordinated steering capability the intraoperative use of a catheter insertion model originating from surgical training has been evaluated. The validation of the insertion model on a simplified test-bed showed a good predictive capability. The final objective is to use such approach for real-time guidance or even robotic catheter control. Speeding up the algorithm for intra-operative use remains therefore a major challenge.**

***Index Terms*—mechanical modeling, surgical simulation, catheter control, navigation assistance**

I. Introduction

In recent years minimally invasive cardiovascular procedures have gained dramatically in popularity. Faster patient recovery, reduced surgical costs and the possibility of using only local anesthesia are amongst the major advantages compared to open heart surgery. In minimal invasive procedures long, thin and flexible instruments or catheters are introduced and advanced into the endovascular system to perform diagnostic or therapeutic tasks. The limited visibility upon and maneuverability of the catheter in combination with the complex and fragile nature of the vasculature has raised the interest in robotic assisted catheterization. More advanced catheters featuring more degrees of freedom (DOFs) than conventional catheters can be controlled robotically hence allowing in principle more precise, repeatable and efficient catheter motion. This potential is at present far from realised as surgeons can only control one DOF at a time. Efficient operation of these devices requires thus still considerable insight and expertise. The knowledge that would be needed to allow coordinated multi-DOF control e.g. needed to closely follow an optimal trajectory inside the vasculature is still lacking. A first requirement is here the presence of realistic models of both the catheter and the vessel wall, formulated in such a way that they allow easy and fast computation of the catheter robot's kinematics.

In the literature a number of interesting algorithms to simulate catheter motion have been proposed. Cotin *et al.* use Finite Element Method (FEM) to model the catheter as a series of connected 3D beam elements[6]. The positions of these beams are geometrically constrained by the vessel model. To take into account the geometric nonlinearities arising from large catheter deformations, the authors propose an incremental FEM approach. This however results in a cumulative error on the catheter shape. Luboz and Wang use mass-spring models for the catheter [9], [11]. Such approaches encounter problems in preserving the constant catheter length as this turns the equations numerically stiff. The catheter can also be modeled as a set of discrete Elastic Kirchhoff Rods [8], [10], but no experimental validation was performed of these models. Finally in [7] the authors designed a method for catheter simulation searching the minimum energy state of a catheter that is represented as a set of rigid links interconnected with springs. Because of the extensive validation of this algorithm and the need for an accurate simulation, this last algorithm is selected and adjusted for catheter position control. In the remainder of the paper, the adjusted simulation model is described in subsection II-A. The model has been implemented. Experimental validation and results are discussed in subsection II-B. Finally, in section III the paper is concluded and directions for further work are discussed.

II. Minimum energy model

While the catheter is inserted into the vasculature, it flexes and bends passively adapting its shape to the geometry of the vasculature. The shape and tip position are largely dependent on the forces that act on the catheter, but also on its motion history. Konings *et al.* derived a semi-analytic simulation that can accurately predict the motion of a catheter inside the vasculature [1], [2], [3], [4], [7]. Starting from a known geometrical and material model of the vessel, the algorithm calculates the catheter shape after a forced motion of the catheter such that the total potential energy of the combined catheter and vessel wall is minimal. The simulation algorithm has been designed for training purposes. This abstract extends its applicability to steering of active catheters.

A. The relaxation algorithm

Under the assumption of high axial and torsional stiffness, a catheter can be represented as a series of i rigid links of constant length λ_i connected by spherical joints (Fig.1.a). An angular spring is attached at each joint as illustrated in Figure 1.b. The original catheter model of Konings, restricted

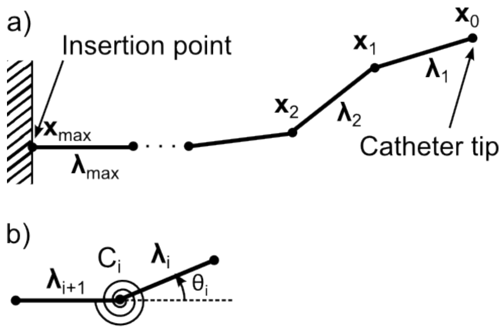

Fig. 1. (a) representation of a catheter as a series of rigid links of length $\boldsymbol{\lambda}_i$ at positions $\boldsymbol{x}_i$ (b) angular springs with stiffness c_i connect the joints.

to the modeling of straight guidewires, was later extended to also include intrinsic curvature and rotation about the catheter axis. The fixed intrinsic curvature angle used to characterize pre-shaped guidewires, is made adaptable here in order to replicate the behavior of active catheters with a proximal DOF and e.g. a locally bending of the catheter tip. After this adaptation an input-output map between the displacements of the actuating cables, embedded in the catheter, and the tip motion is derived. Similarly a change in rotation of the catheter about its longitudinal axis at the proximal side, is achieved by adjusting the internal rotation angle as proposed in [4]. The original approach to represent rotation fails to correctly determine the direction of the intrinsic curvature after deformation of the catheter in interaction with the vasculature. This is due to the fact that the local rotation angle at the active side of catheter is always described w.r.t. to the fixed reference frame placed at the insertion point. To solve this issue, the approach is adapted by attaching a frame to every joint, based on a discrete version of the theory of Bishop frames [5]. The intrinsic curvature at each joint is then expressed easily with respect to these frames. The relaxation algorithm is an iterative minimization algorithm estimating the catheter shape based on the assumption that the equilibrium state corresponds to a minimal energy state of the combined catheter-vessel system. The total energy is thus composed of the vessel energy and the energy of the deformed catheter. The final shape estimate is found after executing an adequate number of relaxation steps. In each relaxation step, all bending angles $\boldsymbol{\theta}_i$ are calculated consecutively, starting from the tip of the catheter (i $=$ 0) and propagating to the proximal end of the catheter and the insertion point. Additional relaxations can be imposed to further refine the shape estimates and obtain more accuracte predictions. The new implementation is evaluated next.

B. Model validation

In order to evaluate the accuracy of the catheter-vessel simulation approach an *in-vitro* experimental test-bed was made from a segmented MR-scan of a human aorta. The projection of the model on a 2D-plane was made and a centerline extracted. A 20mm thick aorta-model was constructed along this centerline. The contour of the aorta was cut out from a 3mm thick polycarbonate plate and embedded in a sandwich structure. An Ethernet GigE Prosilica GC650C with 6mm lens and resolution of 659×493 pixels was placed above the test-bed to compute the ground truth. The camera was placed on a customized mount 720mm above the aorta phantom. Figure 2 shows a raw image obtained from the camera and the results of the segmentation and comparison with the insertion model. The camera images have been segmented and the shape of the catheter has been obtained after the insertion of 700mm into the phantom. The resulting catheter shape obtained from the camera was compared to the position and shape predicted by the insertion model. Two measures have been used to quantify the similarity: the Hausdorff distance d_h and the Root Mean Square (RMS) of the deviation between both shapes d_{RMS}. The results show a RMS deviation stays below 2.5mm whereas the Hausdorff distance is 4.4mm. These findings correspond to the results obtained by the Konings group.

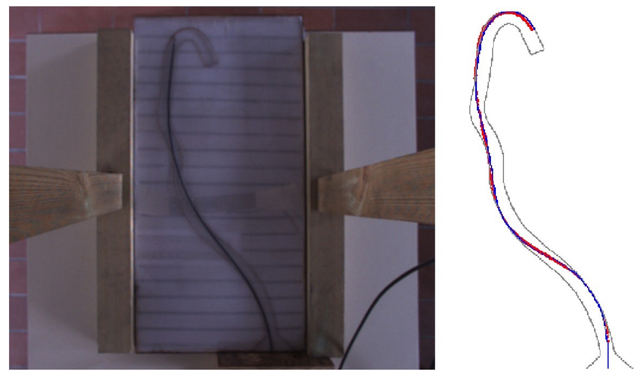

Fig. 2. Raw image of the setup with the test catheter inserted in the 2D aorta mock-up (Left). Overlay of the simulated catheter (blue) over the real catheter (red) for an insertion length of 700mm (Right).

III. Conclusion

In this paper a catheter insertion model proposed by Konings has been evaluated. The simulation model iteratively searches for a quasi-static equilibrium state of a catheter and vasculature after a set of forced actions of the catheter robot. The model was expanded to simulate catheter insertion, retraction, rotation and distal bending of the catheter tip. In validation experiments the catheter shape obtained by the insertion model was compared to the measured catheter shape. A good fidelity of the model was obtained. In future work the model will be applied for actual catheter position control. Further effort needs to be paid to speed up computations though as current computations are far from real-time.

Acknowledgments

This research has been supported by the Commission's 7th Framework Programme FP7-ICT, by the project CASCADE under grant agreement No.601021.

References

[1] T. Alderliesten, P. A N Bosman, and W.J. Niessen. Towards a real-time minimally-invasive vascular intervention simulation system. *Medical Imaging, IEEE Transactions on*, 26(1):128–132, 2007.

[2] T. Alderliesten, M.K. Konings, and W.J. Niessen. Simulation of minimally invasive vascular inventions for training purposes. *Comput Aided Surg*, 9(1–2):3–15, 2004.

[3] T. Alderliesten, M.K. Konings, and W.J. Niessen. Robustness and complexity of a minimally invasive vascular intervention simulation system. *Medical Physics*, 33(12):4758–4769, 2006.

[4] T. Alderliesten, M.K. Konings, and W.J. Niessen. Modeling friction, intrinsic curvature, and rotation of guide wires for simulation of minimally invasive vascular interventions. *Biomedical Engineering, IEEE Transactions on*, 54(1):29–38, 2007.

[5] Richard L. Bishop. There is more than one way to frame a curve. *The American Mathematical Monthly*, 82(3):246–251, 1975.

[6] S. Cotin, C. Duriez, J. Lenoir, P. Neumann, and S. Dawson. New approaches to catheter navigation for interventional radiology simulation. In *Proceedings of the 8th international conference on Medical image computing and computer-assisted intervention - Volume Part II*, MICCAI'05, pages 534–542, Berlin, Heidelberg, 2005. Springer-Verlag.

[7] M.K. Konings, E.B. Kraats, T. Alderliesten, and W.J. Niessen. Analytical guide wire motion algorithm for simulation of endovascular interventions. *Medical and Biological Engineering and Computing*, 41(6):689–700, 2003.

[8] Shun Li, Jing Qin, Jixiang Gao, Yim-Pan Chui, and Pheng-Ann Heng. A novel fem-based numerical solver for interactive catheter simulation in virtual catheterization. *Journal of Biomedical Imaging*, 2011:3:3–3:3, jan 2011.

[9] Vincent Luboz, Rafal Blazewski, Derek Gould, and Fernando Bello. Real-time guidewire simulation in complex vascular models. *Vis. Comput.*, 25(9):827–834, jul 2009.

[10] Wen Tang, Pierre Lagadec, Derek Gould, Tao Ruan Wan, Jianhua Zhai, and Thien How. A realistic elastic rod model for real-time simulation of minimally invasive vascular interventions. *Vis. Comput.*, 26(9):1157–1165, sep 2010.

[11] F. Wang, L. Duratti, E. Samur, U. Spaelter, and H. Bleuler. A computer-based real-time simulation of interventional radiology. In *Conf Proc IEEE Eng Med Biol Soc*, 2007.