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Design of Smart Catheter for Vascular Applications Using Optical Fiber Sensor

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Abstract : In the field of minimally invasive, smart medical instruments such as catheters and guidewires are typically used at a remote distance to gain access to the diseased artery, often negotiating tortuous, complex, and diseased vessels in the process. Three optical fiber sensors with a diameter of 1.5mm each that are 120° apart from each other is proposed to be mounted into a catheter-based pump device with a diameter of 10mm. These sensors are configured to solve the challenges surgeons face during insertion through curvy major vessels such as the aortic arch. Moreover, these sensors deal with providing information on rubbing the walls and shape sensing. This study presents an experimental and mathematical models of the optical fiber sensors with 2 degrees of freedom. There are two eight gear-shaped tubes made up of 3D printed thermoplastic Polyurethane (TPU) material that are connected. The optical fiber sensors are mounted inside the first tube for protection from external light and used TPU material as a prototype for a catheter. The second tube is used as a flat reflection for the light intensity modulation-based optical fiber sensors. The first tube is attached to the linear guide for insertion and withdrawal purposes and can manually turn it 45° by manipulating the tube gear. A 3D hard material phantom was developed that mimics the aortic arch anatomy structure in which the test was carried out. During the insertion of the sensors into the 3D phantom, datasets are obtained in terms of voltage, distance, and position of the sensors. These datasets reflect the characteristics of light intensity modulation of the optical fiber sensors with a plane project of the aortic arch structure shape. Mathematical modeling of the light intensity was carried out based on the projection plane and experiment set-up. The performance of the system was evaluated in terms of its accuracy in navigating through the curvature and information on the position of the sensors by investigating 40 single insertions of the sensors into the 3D phantom. The experiment demonstrated that the sensors were effectively steered through the 3D phantom curvature and to desired target references in all 2 degrees of freedom. The performance of the sensors echoes the reflectance of light theory, where the smaller the radius of curvature, the more of the shining LED lights are reflected and received by the photodiode. A mathematical model results are in good agreement with the experiment result and the operation principle of the light intensity modulation of the optical fiber sensors. A prototype of a catheter using TPU material with three optical fiber sensors mounted inside has been developed that is capable of navigating through the different radius of curvature with 2 degrees of freedom. The proposed system supports operators with pre-scan data to make maneuverability and bendability through curvy major vessels easier, accurate, and safe. The mathematical modelling accurately fits the experiment result.

Keywords : Intensity modulated optical fiber sensor, mathematical model, plane projection, shape sensing.
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