Development of an Innovative Sleeve-Based Robotic Catheter Driver

O. Al-Ahmad[1], M. Ourak[1], S. Jeanquart[1], N. Deserranno[1], F. Bernhard[2], Y. Kassahun[2], B. Yu[1], E. Vander Poorten[1]

[1]*KU Leuven University, Department of Mechanical Engineering, Leuven, Belgium,*
[2]*Robotics Innovation Center (DFKI GmbH), Bremen, Germany*
omar.alahmad@kuleuven.be

INTRODUCTION

Cardiovascular diseases (CVD) form the most common cause of death in the EU. Minimally Invasive Surgery (MIS) and robotic catheterization are becoming more popular therapies to treat CVD. MIS approaches are especially attractive as they significantly aid in reducing intra- and post-procedural complications [1]. Radio-frequency Ablation (RFA) by means of catheterization interventions is a rather common procedure within this context. One of its applications is in the treatment of Atrial Fibrillation (AF). However, this procedure is not risk-free. Some of the complications may include inflammation, cardiac perforation and cerebrovascular accidents [2]. It is therefore crucial to develop assistive technologies that help minimize risks and aid interventionalists in achieving maximum success rates. Robotic catheter driver systems have been developed within this framework. Systems like the Sensei™ and the Magellan™ from Hansen Medical or the Niobe® driver from Stereotaxis are commercially available. These systems usually work with special types of catheters and are expensive. Most catheter drivers mainly rely either on friction rollers and belt transmissions [3]–[5] or mechanical gripping and translation [6]–[9]. A dis-advantage of these drive methods is that they apply large stresses locally upon the catheter and may cause damage to the catheter itself or its internal components (sensors, actuators or wirings). The focus of this paper is on a new type of catheter driver that uses pneumatically-actuated sleeve-based grippers (see Figure 1). These grippers exert evenly distributed forces along the length of the catheter, preventing damage and slippage.

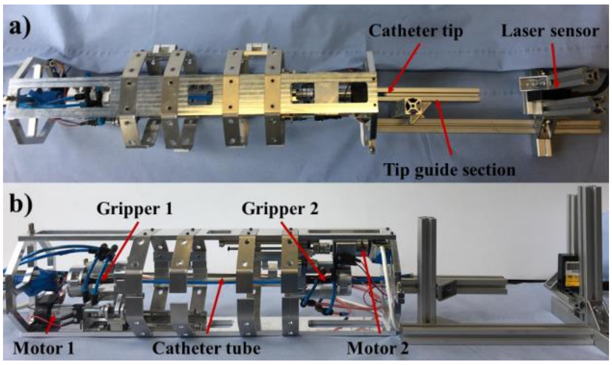

Figure. 1. Catheter driver system with pneumatically-actuated sleeve-like grippers, a) top view b) side view.

MATERIALS AND METHODS

The catheter driver is required to achieve an infinite continuous stroke resulting in the smooth translation of the catheter. In order to achieve this continuous motion, an optimized gripping strategy must be developed. This strategy combines the efficient gripping of the sleeve-like grippers and their corresponding translation. The gripping mechanism and strategy are outlined below.

Gripping mechanism: A braided sleeve fitted within the pneumatic cylinders (FESTO ADVC-6-10-A-P) is tensioned when the cylinders extend. The sleeve's elongation causes a reduction in its diameter, hence permitting contact between the sleeve and the embedded catheter. In effect, the distributed contact force creates large friction between the sleeve and the catheter so that slippage is prevented. The gripper block (incorporating the pneumatic cylinder and the sleeve) is mounted onto a guiding rail. A ball screw system is used for the translation of the gripper block. The ball screw is linked to a DC motor through an appropriate transmission.

Gripping strategy: The grippers are placed on opposite sides such that they approach each other when extending-/translating. The translation strategy of the catheter is somewhat similar to peristaltic motion and is explained as follows (see Figure 2): 1) starting from the home position, gripper 1 grips and gripper 2 releases 2) both grippers start to move outwards (gripper 1 at speed (V) and gripper 2 at speed (V·α), where $\alpha > 1$) 3) gripper 2 reaches the end of its stroke 4) just before gripper 1 reaches the end of its stroke, gripper 2 moves inwards (in the same direction as gripper 1) at speed (V) 5) gripper 2 grips (both grippers are now gripped) 6) gripper 1 reaches the end of its stroke and releases 7) both grippers move inwards (gripper 2 at speed (V) and gripper 1 at speed (V·α), where $\alpha > 1$). The cycle is then repeated until the desired catheter tip position is reached.

Other gripping-based systems [6]–[8] have limited strokes, where a temporary interruption in gripping is required to return the gripper to its home position and continue translation. This means that there will be a delay at the end of each stroke before resuming motion. On the other hand, the control strategy outlined in this paper provides for a unique advantage. It allows for continuous smooth motion where at all times, at least one of the two grippers is gripped. This type of control has not been implemented before in such applications. The logic and control of the driving mechanism was based on a Finite State Machine (FSM) approach. LabVIEW 2016 software and the NI CompactRIO were used for the implementation. A cascaded controller was implemented to control the grippers' linear position. This also improves the overall system's behavior and helps reject external disturbances such as uneven friction.

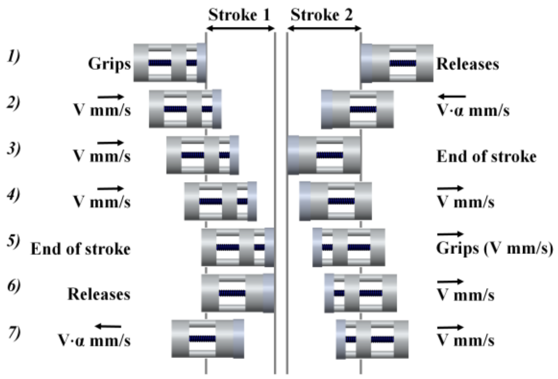

Figure. 2. Illustration of the catheter gripping strategy.

RESULTS

The catheter translation mechanism was tested in an experimental setup as shown in Figure 1. A laser sensor with an accuracy of approximately 40 microns was used to measure the distance between the catheter tip and the sensor. This served as the ground truth for the position of the catheter tip.

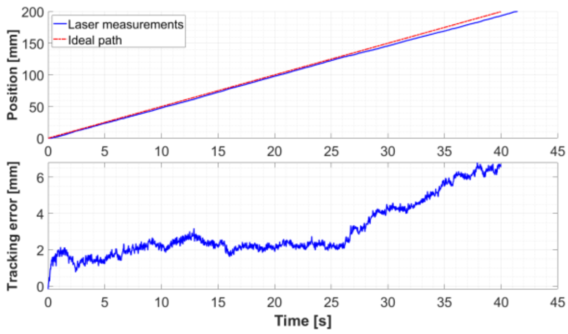

Figure. 3. Catheter tip position measured by the laser sensor throughout the different cycles.

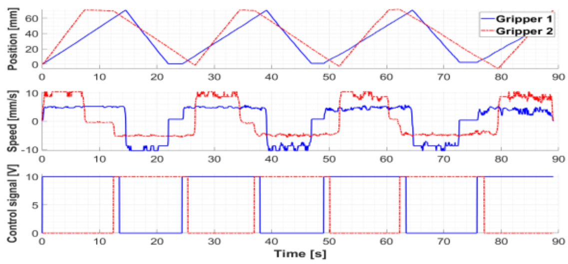

Figure. 4. Position, speed and electrovalve control signal plots.

A targeted travel range of 200 mm was set. Each gripper has a stroke of 70 mm, meaning that approximately 3 cycles are required to reach the setpoint. The position as measured by the laser sensor and the tracking error from the ideal path (at speed = 5 mm/s) is shown in Figure 3. The results are encouraging as they show a proper linear increase in position over time. In addition, the tracking error between the ideal path (at the desired speed) and the actual travelled path shows reasonable deviation. More importantly, there are no evident peaks or jumps in position when the gripping/ungripping action occurs between cycles. This is due to the fact that the transition between grippers only occurs when both grippers are gripped and moving at the same speed (dynamic re-gripping). The position error at the end of the cycles was less than 0.1 mm indicating the driver's high positional accuracy. Figure 4 shows the position and speed measurements of the individual grippers as measured from the encoders. The electrovalve control signals are also shown to indicate when the cylinders are gripped. In this case however, a position setpoint of 420 mm was set (this corresponds to 6 cycles). This was done to have a better illustration of the cycles. The behavior shown in Figure 4 does indeed correspond to the translation mechanism described in the previous section (see Figure 2). In this case, α was chosen to be 2. This can be seen in the plots where speed values fluctuate between 0, 5 and 10 mm/s (in both directions of course).

CONCLUSION AND DISCUSSION

A new type of catheter driver system was developed and evaluated in this paper. A control strategy for gripping-/ungripping between cycles was implemented to minimize positional error and maintain a constant speed at the catheter tip. The results are promising as they illustrate a smooth linear increase in catheter tip position. The positional accuracy of the system was found to be less than 0.1 mm indicating the driver's potential use for intricate cardiothoracic surgeries. The driver's repeatability is yet to be investigated. An improvement to the current mechanical components of the driver system is intended to achieve better positional accuracy at higher speeds (as the current motors have not been optimized for this application yet).

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