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# A Fibre-Optic Catheter-Tip Force Sensor with MRI Compatibility: A Feasibility Study

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*Abstract*— **This paper presents the development of a low-cost, Magnetic Resonance Imaging (MRI) compatible fibre-optic sensor for integration with catheters allowing the detection of contact forces between blood vessel walls and the catheter tip. Three plastic optical-fibres are aligned inside a plastic catheter in a circular pattern. A reflector is attached to a separate small part of the catheter tip, which is connected with a small deformable material to the aligned optical-fibres. In this manner a force at the catheter tip leads to a deformation of the elastic material and thus a modulation of the light yields, this is sent and received through the optical-fibres. An electronic circuit amplifies the retrieved light signal and the output voltage is used to classify the forces on the tip. The materials used are of the shelf and have a low magnetic susceptibility making this sensor fully MRI-compatible and inexpensive. Preliminary, experimental results demonstrated good force linearity in static loading and unloading conditions. The sensor was also tested in an artificial blood artery showing good dynamic response.**

## I. INTRODUCTION

CARDIAC catheterisation is considered to be a minimally invasive technique that is usually carried out under image guidance of X-ray fluoroscopy. Unfortunately, X-ray guided cardiac catheterisation has poor soft-tissue contrast which makes the positioning of guide wires, catheters, balloons, and interventional devices difficult, with the operator relying either on contrast angiographic images taken earlier in the procedure, or a mental image of the anatomy. This poor visualisation of the relevant anatomy is a particular handicap in electrophysiology applications, in which a defined force contact of catheter tip with the myocardial structures is required. This results in prolonged procedure time, increased X-ray dose and a higher risk of complications.

Much interest has grown in recent years in the use of real-time MRI instead of X-ray fluoroscopy as an image-guiding modality for intravascular interventions. It has been shown that interventional MRI is safe and practical in a clinical setting allowing better three dimensional visualization of the anatomy with superior soft tissue contrast, while avoiding ionizing radiation [12]. However, the widespread use of MR-guided cardiovascular interventions has been hindered due to the lack of MR-compatible and patient-safe devices. In particular, materials that can affect the homogeneity of the magnetic field are to be avoided as they distort the quality of images and generate health risks.

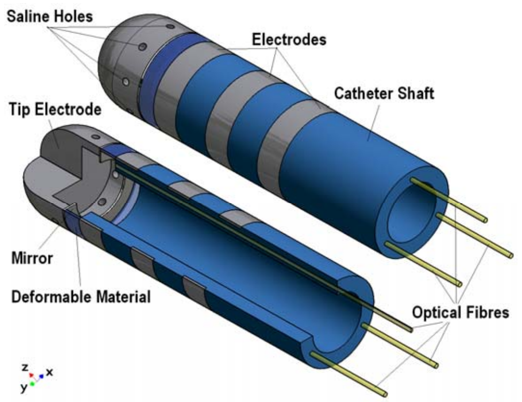

Fig. 1. Drawing views of a 7 Fr. catheter illustrating the proposed concept of the three axes fibre-optic force sensor.

Fibre-optic technology was found to be MRI-compatible, drawing attention in the production of sensors suitable for these kinds of operations. In addition, as optical-fibres are produced in micro metric sizes their use is ideal for integration with catheters [13] an application where the space constraints plays an important role. However, the miniaturisation process often increases the cost of integration of force sensors with a catheter delaying their use and commercialisation.

Consequently, in this paper the feasibility study of a three axes fibre-optic tip catheter force sensor is presented. This sensor adopts a light intensity modulation concept which returns satisfying preliminary results. The use of low-cost, off-the-shelf materials, in accordance with the benefits of a fully MRI compatible sensor makes it ideal for catheters.

## II. BACKGROUND

### A. *Minimally Invasive Surgery (MIS)*

MIS allows surgeons to access the internal anatomy of a patient through small openings. The benefits of that approach are many and they have an affect both to the patient and the hospital [1]. Even though MIS has numerous advantages to present, still there are some drawbacks which make its implementation in theatres difficult [3]. One of the most important is the lack of force feedback

To overcome the drawbacks, robots in surgery have been introduced and their development is playing an imperative

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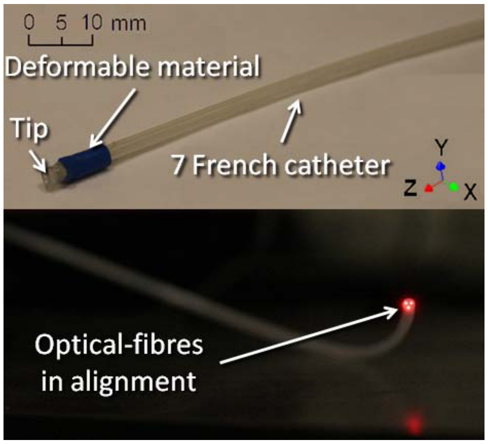

Fig. 2. Top: The fibre-optic sensor inside a 7 French catheter, without Electrophysiology ablation (EP) electrodes. Bottom: The alignment of the optical-fibres inside the same catheter.

role in the advancement of MIS [4]. Today's most renowned robot for surgical applications is the da Vinci™ surgical system (Intuitive Surgical, Sunnyvale, California) [5].

Regardless of any improvement in the accuracy and safety offered by robots in surgery, the loss of haptic feedback still remains an important unsolved issue.

### B. *Catheterisation*

Catheterisation is a minimally invasive approach which targets to offer treatment or examination to tissues and organs using existing routes inside a human body. Routes such as the blood vessels are used to allow thin, long and flexible instruments to reach targeted settings within the body. These instruments are called catheters and their diameter does not exceeding 3-4 mm [7]. The insertion and progression of a catheter into the body is achieved from a small incision on the groin (upper thigh), the arm, or the neck of the patient.

In a catheterisation the restrictions for the size of instruments to be used originates in the size of the blood vessel. Therefore, as cameras are almost impossible to be inserted, other visualisation methods are used. Fluoroscopy and Computed Tomography (CT) are the two most common methods used today by cardiologists. These techniques employ ionising technology, such as X-rays, to represent the inner human structure. However, their use is hazardous for the human body. In addition, the quality of the tissues and organs in the returned images is poor. In order to enhance them the catheter has to inject a contrast medium inside the area of interest.

Lately, scientists are interested in substituting these methods with others which have distinct advantages; one of these methods is the MRI. MRI is making use of magnetic fields to produce the images. As a result, these images are giving three dimensional representation of the internal body structure with superior quality and without emitting hazardous ionising radiations.

Despite the advantages of an MRI scanner, the use of tools and instruments inside its area of operation which contain materials that could affect the homogeneity of the magnetic field must be avoided. Furthermore, the insertion of conductive wires can potentially work as an MR-antenna, which can result in potential heating effects at the tip of the wire during MR-scanning. Hence, metal materials are ineffective, as either distort the images, producing artefacts, or heating up effects putting in health risks the patients [8]-[10].

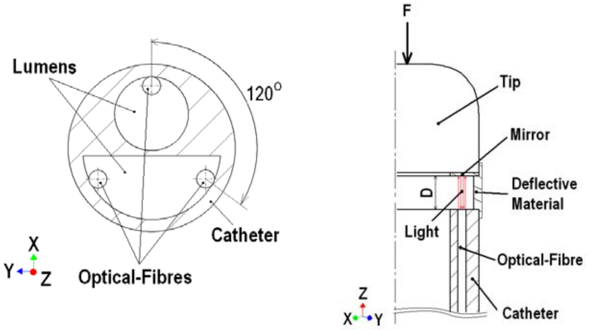

Fig. 3. Left: A horizontal section view of the 7 Fr. catheter showing the shape of the two lumens and the position of the optical-fibres. Right: A vertical partial section view of the fibre-optic catheter sensor showing one of the three optical-fibres emitting and receiving light at a distance D from the mirror.

### C. *Force Feedback*

Interventional cardiologists are often able to sense the interaction of the catheter tip with the internal structures (e.g. blood vessels, atrium of the heart) while performing a catheterisation. That haptic feedback is often used to realise the position and the manoeuvres of the catheter requiring usually extensive training to achieve this expertise. Although a contact of the catheter with internal structures can be felt by the interventional cardiologist, the distinction of the involved forces is a difficult task. These forces are a combination of two secondary forces. The one originates from the friction of the catheter with the blood vessel walls and the other from the contact of the catheter-tip with the blood vessels [2].

Several systems have been developed to enhance catherisations, like Sensei™ robotic catheter system (Hansen Medical, Inc., Mountain View, California) [6] and the recently developed TactiCath (Endosense SA, Geneva, Switzerland) [11]. Nevertheless, most of the solutions given today by scientist do not take into account the ease in manufacturing, the costs for production and the MRI-compatibility.

In every surgical robotic system which deals with catheterisation realisation that the information carried from the interaction forces between the catheter and the blood vessels is imperative. Therefore, in this paper a new approach for detecting the contact forces from the tissue-catheter interaction is discussed. In extent, a fibre-optic sensory system is presented in a feasibility study, as a low-cost and MRI compatible solution.

## III. LOW-COST FIBRE-OPTIC FORCE SENSOR

### A. *Sensor Structure*

The sensor consists of three plastic fibre-optic cables of 250 μm in diameter, a reflective circular mirror of 2.3 mm in diameter and 0.4 mm thick with a hole in the middle, a deformable connecting material (natural latex) and a 7 Fr. plas-

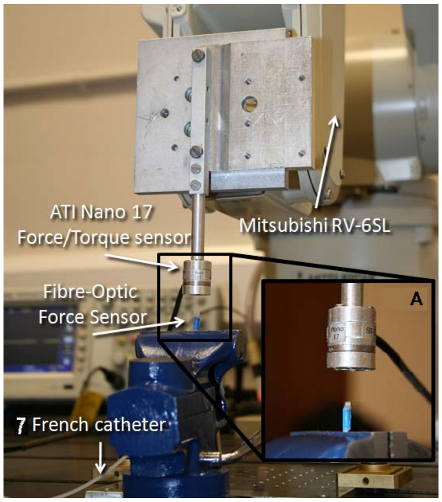

Fig. 4. Correlating the forces applied to the fibre-optic sensor with the voltage output of the optical-fibres. The test bench and a close-up view (A) of the nano17 and the produced sensor.

tic Pebax-6333SA catheter with two lumens (Arkema Inc., France). The sensor integrated with the catheter is shown in fig.2 (top). The plastic optical-fibres are aligned inside the two lumens in such way to create a circular pattern with 120 degrees spacing between them. The optical-fibres illuminating inside the catheter can be seen in fig. 2 (bottom), whereas in fig. 3(left) the alignment within the lumens of the catheter is shown. In addition, a short in length part of the plastic catheter is cut prior to the optical-fibres alignment, in order to be used as the tip of the catheter-sensor. The circular mirror is positioned concentrically at one of the two cylindrical flat surfaces of the short catheter part, leaving the way free to the lumens.

The deformable material is obtained in a form of a thin film and is wrapped and glued concentrically around the main part of the catheter and the short catheter part, which accommodates the mirror. After the wrapping the catheter's tip diameter increased and reached 2.6 mm. With this technique the two parts are connected leaving 1 mm of space between the aligned optical-fibres and the reflector. The distance denoted with the letter 'D' in fig.3 (right) shows the free space previously described.

### A. *Principle of operation*

The principle of operation for this fibre-optic scheme is based on light intensity modulation caused by the change in distance of the reflector when a force is applied at the tip of the catheter. Each one of the optical-fibres is interrogated by a super bright red LED which operates at 650 nm wavelengths. Fibre-optic couplers are employed to emit and receive the reflected light through the same single integrated optical-fibre within the catheter. The couplers are used to ensure less occupied space by optical-fibres within the catheter and to increase the amount of received/reflected light signal. At the end of the optical couplers a dedicated amplifier electronic circuit is responsible to collect the light signal, using SFH 250V (Infineon Technologies Ltd, UK) photodiode detectors. The light signal is converted in a voltage signal and passes through two stages of amplification. The two amplification stages ensure reduction of the electrical noise as 1st order low-pass Butterworth filters exist between and after amplifications. In this manner the noise is limited to a peak-to-peak value of 60 mV.

The three optical-fibres are positioned in such way to return, after calibration, the vector of the force in a Cartesian coordinate system with X, Y and Z components. The Z component is calculated from the average change in distance 'D' of the reflected light from all the optical-fibres when a force is applied in the tip vertically. The remaining X and Y components occur when forces are applied at an angle from the vertical Z axis at the tip.

## IV. LINEARITY AND HYSTERESIS EXPERIMENT

### A. *Test Bench and Setup*

To investigate the force output of the sensor in axial loading, a test bench was employed, as shown in fig.4. The test bench consisted of a vice, which act as the rigid support for the catheter, an ATI 6 axes force/torque sensor (ATI Industrial Automation, Inc., NC, USA), a robotic manipulator (Mitsubishi RV-6SL), the optical-fibre amplifying circuit and a NI USB-6211 data acquisition card (National Instruments Corp.).

The sensor was placed in the support vertically, having the tip looking upwards and leaving 8 mm to stand out. The ATI force sensor was mounted on the manipulator aligned above the developed sensor (see fig. 4). Using this configuration the manipulator could translate with a constant low speed in the axial direction and towards the fibre-optic sensor deforming the elastic connecting material, closing slowly the gap between the reflector and the light emitting optical-fibres. The light intensity variation, after the signal amplification, was constantly recorded using the data acquisition card. In addition, the force measurements obtained by the ATI sensor, while exerting force to the developed sensor, were also recorded.

### B. *Experimental Results*

The recorded force signals (ATI sensor) and voltage signals (light amplifier) were correlated returning a good linear force response and a working range for the sensor from 0 to 1.1 N in axial loading. The sensor also demonstrated good sensitivity due to the elastic properties of the deformable material used. In addition, the resolution due to noise effects is limited to 0.04 N. The responses were obtained after loading and unloading the fibre-optic sensor three times.

## V. ARTIFICIAL BLOOD ARTERY EXPERIMENT

### A. *The Artificial Blood Artery*

To test the efficiency of the newly developed fibre-optic sensor, a thin flexible transparent tube with 4 mm inner diameter was used as an artificial blood artery in an ex-vivo experiment. The catheter with the optical-fibre force sensor was inserted in the artificial blood artery, which consists initially of a curved path followed by a junction that splits the artery in two separate paths. The artificial artery is

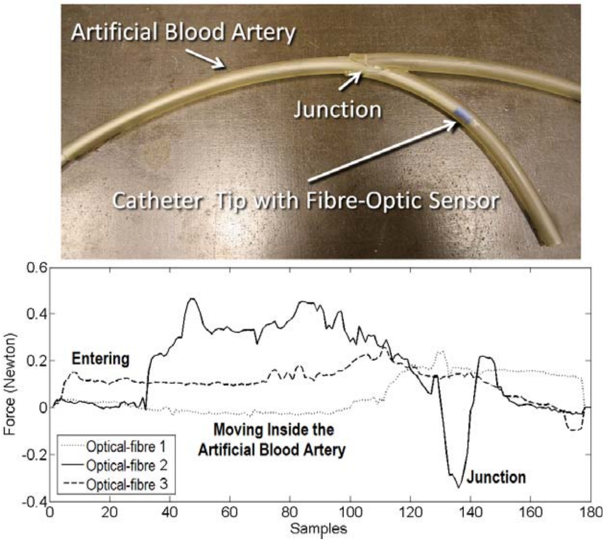

Fig. 5. Top: The insertion of the catheter with the fibre-optic sensor inside an artificial blood artery and Bottom: the resultant forces from each optical-fibre at every stage of the catheters movement.

shown in fig. 5 (top). The insertion and the forwarding of the catheter were made manually to increase the accuracy of the experiment.

### B. *Experimental Results*

The experimental results from the insertion of the catheter inside the artificial blood artery are presented in fig. 5 (bottom). There one can observe the force outputs of every optical-fibre in different stages of insertion and forwarding.

Entering the blood artery some negligible force variations occurred of less than 0.2 N. However, forwarding the catheter through the curved path caused variable force fluctuations of increased magnitude. At the junction of the artery a negative pick force was captured by one of the optical-fibres indicating that the catheter encountered resistance. For the last part, the forces point out a smoother motion without big resistance.

## VI. DISCUSSION AND FUTURE WORK

The fibre-optic sensor was tested only on axial loading and unloading. In the future, one aim is to examine and calibrate all three axes of the sensor performing trials on the sensor's tip axialy and radialy at different angles.

The hysteresis level is too high to enable accurate force measurements.This could be corrected by testing deformable materials of different properties or by adjusting the distance of the reflector from the tip.

The electrodes for an Electrophysiology (EP) sesning or ablation catheter have not yet been placed on the catheter. Therefore, measurements with the electordes could affect the behaviour of the sensor and this is something that must be investigated. In addition, other methods for the optical-fibre alignment must be also investigated in order to minimise the errors in force readings due to missalignemnets.

The sensor was produced fully of MR-compatible materials, making its use possible in an MRI enviromnet. Nevertheless, the MRI-compatibility must be validated under an MRI scanner in order to observe the artefacts and the image distortion levels produced.

## VII. CONCLUSION

Experimental results previously reported demonstrate well the feasibility of this fibre-optic force sensor. The proposed fibre-optic force sensor for catheters was tested in axial loading and unloading conditions returning satisfying preliminary results with a linear force response, a wide working range for such applications and good resolution. However, the hysteresis cycle obtained indicates that there is room for improvement. The phantom experiment of the insertion inside the artificial blood artery proved true for this feasibility study, demonstrating the sensor's use and its force feedback.

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