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An optical fibre dynamic instrumented palpation sensor for the characterisation of biological tissue

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ABSTRACT

The diagnosis of prostate cancer using invasive techniques (such as biopsy and blood tests for prostate-specific antigen) and non-invasive techniques (such as digital rectal examination and trans-rectal ultrasonography) may be enhanced by using an additional dynamic instrumented palpation approach to prostate tissue classification. A dynamically actuated membrane sensor/actuator has been developed that incorporates an optical fibre Fabry–Pérot interferometer to record the displacement of the membrane when it is pressed on to different tissue samples. The membrane sensor was tested on a silicon elastomer prostate model with enlarged and stiffer material on one side to simulate early stage prostate cancer. The interferometer measurement was found to have high dynamic range and accuracy, with a minimum displacement resolution of ±0.4 μm over a 721 μm measurement range. The dynamic response of the membrane sensor when applied to different tissue types changed depending on the stiffness of the tissue being measured. This demonstrates the feasibility of an optically tracked dynamic palpation technique for classifying tissue type based on the dynamic response of the sensor/actuator.

1. Introduction

Prostate cancer is the most commonly diagnosed cancer in men [1]. In common with other cancers, early diagnosis improves the possible outcome for the patient. At present diagnosis of prostate cancer is carried out using four main methods: digital rectal examination (DRE); a prostate-specific antigen (PSA) blood test; prostate biopsy, and trans-rectal ultrasound (TRUS), often incorporating trans-rectal sonoelastography (TRSE).

DRE is a straightforward but subjective test, where the prostate is palpated using the fingertip. Palpation reveals if the prostate is enlarged, and may also reveal the presence of hard nodules which are indicative of cancer [2]. DRE is highly subjective and depends strongly on the skill and experience of the medic performing the examination [3]. In addition, DRE may only have higher levels of accuracy when prostate cancer is at a more advanced stage, which limits its utility as a tool for early stage disease detection. Alternatively a blood test designed to identify high levels of prostate-specific antigen (PSA) for prostate cancer diagnosis may offer earlier detection. Unfortunately the use of the PSA test has been subject to a high rate of false-positive results, leading to unnecessary surgery [2]. In addition, some types of cancer may not cause the production of PSA, which further reduces the reliability of the test. A positive result based upon palpation or PSA tests often results in a prostate biopsy. In this procedure needles are inserted into the prostate and core samples of the gland are removed for histological analysis. The samples are assessed using the Gleason Grade for tissue quality [4] and following these tests, a patient may be recommended for surgery. TRUS and TRSE [5] are also used to diagnose the extent of prostate cancer. In a TRUS examination, the ultrasound transducer is inserted into the rectum and images the prostate *via* its posterior surface. Some types of tumour are visible as anechoic regions in the ultrasound image. TRSE adds a coloured overlay showing tissue stiffness to the image captured using TRUS. In most TRSE probes, an inflatable cuff is attached to the protective sheath over the probe. The cuff is inflated and deflated, usually by hand, to compress and release the tissue around the probe. The

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changes in the image between compression cycles are processed to produce a colour map of (usually relative) stiffness of the tissue in the prostate.

A primary problem with these four common diagnostic methods is low sensitivity and specificity. DRE is unlikely to be able to distinguish small nodules of potentially malignant cancer. A biopsy may miss the cancerous regions of the gland altogether, resulting in a misleading assessment of the type and extent of cancer present. Failures in these diagnostic tools mean that some men undergo unnecessary prostate surgery.

Inadequacies in the current diagnostic tools for prostate cancer diagnosis have led to the development of a dynamic instrumented palpation (DIP) [6] device to measure prostate stiffness and diagnose disease type based on the mechanical properties of the tissue. A DIP device palpates the prostate gland at a controlled frequency and allows the dynamic and static behaviour of the tissue to be measured. This allows measurement of the shear modulus and Young's modulus of the prostate gland, both of which can be used to identify stiffer regions indicative of prostate cancer [7].

A DIP device made in this way can be inserted rectally and a pressure deformable membrane used to palpate the posterior surface of the prostate gland in a similar manner to current DRE practice. The advantage of the device over DRE is that a *quantitative* measurement of stiffness is given that can be compared to other measurements of prostate stiffness and used to diagnose more accurately the presence of prostate cancer.

There have been other attempts at creating a resonant sensor system for measuring the stiffness of the prostate gland. Most other groups have used a resonant actuator that is mounted above an *ex vivo* tissue sample [8–10]. These usually consist of a controlled motion stage linked to a load cell measuring the load applied to the sample. A primary disadvantage of most resonant sensor systems is that the sensor actuator and sensing system are too large to be used *in vivo*.

However a challenge remains in miniaturising the instrumentation used for monitoring the deflection of the deformable membrane. An electrical strain gauge (for example) bonded to the sensor membrane could measure strain as a function of motion but would increase its inertia, which may reduce its sensitivity to small motions. In addition, the strain gauge dimensions limit sensor miniaturisation. An alternative approach is to use optical techniques to monitor the membrane deflection. An optical fibre-based approach is highly miniaturisable, since the size of the measurement point is dictated by the sub-millimetre diameter of the fibre. The non-contact nature of the measurement also means that the measurement system does not influence the motion of the dynamic sensor. This allows the creation of smaller scale sensors that may be used to measure the micro-mechanical properties of tissue.

Therefore, in this paper, we designed and manufactured a prototype fibre optic membrane sensor (the "p-finger") based on a Fabry–Pérot interferometer. A DIP device was developed with a flexible membrane that is inflated and deflated at a controlled frequency. The device was tested on a model prostate gland with a unilateral enlarged region simulating early stage prostate cancer. The relative stiffness of the two sides of the model prostate gland was evaluated by comparing the change in dynamic response of the membrane when it is pressed on sites with and without the simulated cancerous region.

2. Sensing principle

The p-finger consists of a dynamically actuated flexible membrane. The displacement of the membrane is measured using a fibre optic interferometer mounted beneath the membrane to create a Fabry–Pérot interferometer [11]. The p-finger is pressed on to a tissue sample and the change in the dynamic displacement response of the membrane is measured. The change in membrane response is related to the mechanical properties of the tissue being measured. In principle, this allows regions of different tissue types to be distinguished based on the change in measured membrane behaviour.

Fabry–Pérot interferometer-based sensor systems have had previous medical sensor applications. In [12] this type of sensor was used to give force feedback during vitreoretinal microsurgery. A Fabry–Pérot device with a MEMS membrane pressure sensor has also been used to monitor blood flow pressure in the heart [13]. An additional application includes sensing the pressure changes in the pharynx during swallowing [14].

There are various other optical fibre-based sensors which can be used to detect displacement and strain. Fibre-Bragg grating sensors are extensively used but potentially too large for this application [15]. Intensity-based optical fibre sensors can have repeatability problems due to connector losses [16] which do not affect the sensor reported here. Other membrane-based optical sensors have also been developed for non-medical applications. These include a micromachined silicon diaphragm sensor used for pressure measurement [17] and a peninsula-structured diaphragm with a piezoresistive pressure sensor [18].

The deflection of the p-finger membrane can be accurately monitored using interferometry. Light is reflected from the membrane

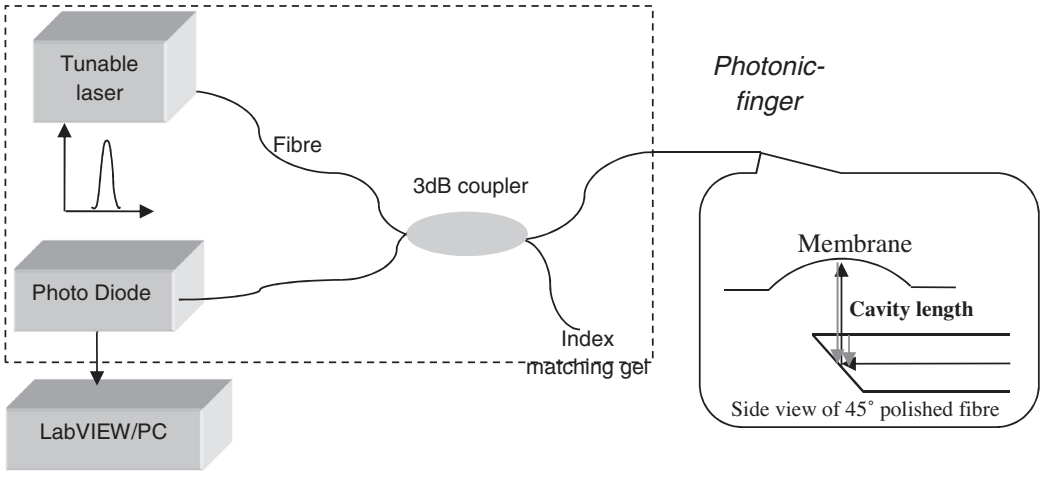

Fig. 1. Left: a schematic of the optical interrogation system, where the tuneable source is incident on the sensor *via* a 3 dB 2 × 2 coupler. The coupler allows the reflected signal to be directed onto a photodetector. Right: the details of the cavity formed between the membrane and a 45° polished fibre.