Miniaturised optical fibre based palpations instrument for minimally invasive surgery

IOP Conf. Series: Journal of Physics: Conf. Series 1151 (2019) 012014 doi:10.1088/1742-6596/1151/1/012014

Miniaturised optical fibre based palpations instrument for minimally invasive surgery

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Abstract. The lack of tactile and force perception during robot-assisted surgeries could lead to application of inadvertent forces resulting in tissue trauma and accidental tissue damage. In order to perform surgical procedures within tight spaces surrounded by sensitive soft tissues, surgeon's ability to manoeuvre instruments with precision and control must be enhanced. Further, the tools with built-in tactile and force sensors enable surgeons to investigate surrounding tissues to determine surgical margins for dissection. This paper proposes a novel optical fibre based tactile probe capable of modelling tool tissue interactions to estimate tissue abnormalities. Tissue stiffness is estimated through an indentation technique. The proposed method allows rapid acquisition of tactile data as the instrument rolls over tissue surface in a near frictionless manner. The probe can concurrently measure both indentation force and indentation depth, which can be combined to develop a pseudo-colour stiffness image of the investigated tissue with abnormal regions clearly highlighted.

1. Introduction

Touch is at the core of personal experience. Touch provides both cutaneous (tactile) and kinaesthetic (force) information and is an essential feature in object manipulation. Tactile feedback contains information about the contact (i.e. contact status, contact force, contact point or area, slippage and vibration) and can be used to derive mechanical properties of the object: object stiffness, surface texture, and surface frictional coefficient. Similarly, the kinaesthetic feedback is necessary to improve controllability and manoeuvrability. Robot-assisted surgical systems currently in clinical use suffer from the lack of tactile and force feedback and it is a major hindrance for extending the applications of such systems to perform more delicate surgical procedures. Without tactile and force feedback, surgeon cannot feel the surgical field during a surgery. This greatly increases the surgery time and surgeons have to undergo extensive training in simulated environments before using existing robot-assisted surgical systems [1]-[3]. Further, the lack of tactile feedback limits the ability of a surgeon to investigate internal body organs to identify abnormal regions to determine margins for dissection. There is also enough evidence in the literature that the loss of tactile and force feedback also leads to increase in tissue trauma and accidental tissue damage [4].

One possible approach to compensate for loss of tactile and force feedback is the use of imaging techniques to visualize the surgical field and characterize tissue properties. Imaging techniques such as magnetic resonance imaging (MRI) and computer tomography (CT) could be used to develop a roadmap showing the location of tumours in relation to the surrounding environment, including nerves and arteries. Certain specialized MRI techniques such as magnetic resonance spectroscopy (MRS) can be used to analyse even the functional properties of cancers including their chemical structures [5].

However, as MIS surgical systems currently in clinical use are not MRI compatible. Therefore, such imaging techniques must be applied prior to the start of a surgery. In order to use the generated preoperative images during the surgery, real time mapping of the intraoperative position of surgical instruments into preoperative imaging is necessary. Although preregistration and mapping works well in rigid areas such as bones and skull, the procedure is more challenging when soft tissues are involved. This is mainly due to the deformability of soft tissues and tissue shift that may happen during a surgical procedure [6]. To use MR imaging techniques intraoperatively, surgical robotic systems and the orthopaedic hardware used in MRI scanners need to be MR compliant. However, currently available robotic assisted surgical systems such as the da Vinci are not MR compliant and cannot be used intraoperatively.

Intraoperative ultrasound (IOUS) is a technique that can be used to visualize the surgical field during an operation. Although this is one of the most cost effective techniques, images obtained through IOUS are relatively poor in quality [7] and may not be effective in identifying surface lesions that are less than 1cm in diameter [8]. Optical coherence tomography (OCT) is another technique that can be used to visualize subsurface abnormalities with very high resolution. However, OCT's capability in detecting tumours is limited as the penetration depth of OCT is only 1-2mm beyond the organ surface.

Another approach to differentiate sub surface tumours from healthy tissues is the use of palpation technique within the laparoscopic surgery. However, palpation with long thin laparoscopic instruments with limited manoeuvrability is not an effective way to locate tumours buried under tissue surfaces. Such methods can be time consuming and especially with the limited perception of transmitted force signals, they could cause damage to the delicate tissues of the internal organs [9]. Using remote palpation techniques with probes equipped with tactile sensors [10]-[12] could be a better choice in such situations. These probes, when in contact with tissue, measure the distribution of pressure across the tissue to characterize its properties and localize tumours. Further, the information gathered at the surgical site could be relayed to the surgical console to recreate tactile stimuli at the surgeon's fingertips. A number of attempts to develop tactile sensor for MIS has been reported in the literature [13]-[15]. Although, aforementioned tactile sensors have successfully proven their ability to acquire tactile information they are mostly suitable for localized tissue palpation. Acquiring tactile data over a large tissue area could be time consuming, as palpation is usually conducted in a discrete manner. Sliding such probes over tissue surfaces to generate continuous maps of stiffness variation could result in excessive tangential forces that may damage sensitive tissue or the tactile sensor itself. Hence acquiring tactile information over a large area should either be done through a tactile array [16] or using a probe that can rapidly move over the tissue surface. The tactile sensor presented in [17] uses a rolling indentation technique with a force sensitive wheeled probe to obtain stiffness distribution of a larger tissue in a relatively short period of time. However, in this method, it is essential to maintain a constant indentation depth throughout the palpation activity. Although this could be achieved through the pre-registration of the tissue surface, it could be time consuming and may introduce errors due to tissue shifts during palpation.

2. Air-float Palpation Probe

With the aim of addressing issues mentioned in the previous section, the authors have developed and validated a novel MRI compatible palpation instrument for MIS applications. Initial research leading to this is available in [18]-[20]. The proposed instrument is designed to measure stiffness distribution of a soft tissue while sliding over the tissue surface in a near frictionless manner. A novelty of the probe is its ability to measure indentation depth for irregularly-shaped tissue profiles which are commonly experienced during surgery. Since tumours are often harder than the surrounding tissue, the proposed probe can intra-operatively aid the surgeon to rapidly identify the presence, location and size of the tumours through the generation of a tissue stiffness.

Although the features of the proposed instrument is very promising for MIS applications, the diameter of the probe still too large for a standard trocar port. Therefore, this paper presents a modified version of the air-float palpation probe (see Figure 1). The new probe is only 0.9mm in diameter and

provides better performance in tumour identification as it possess better pressure regulation characteristics.

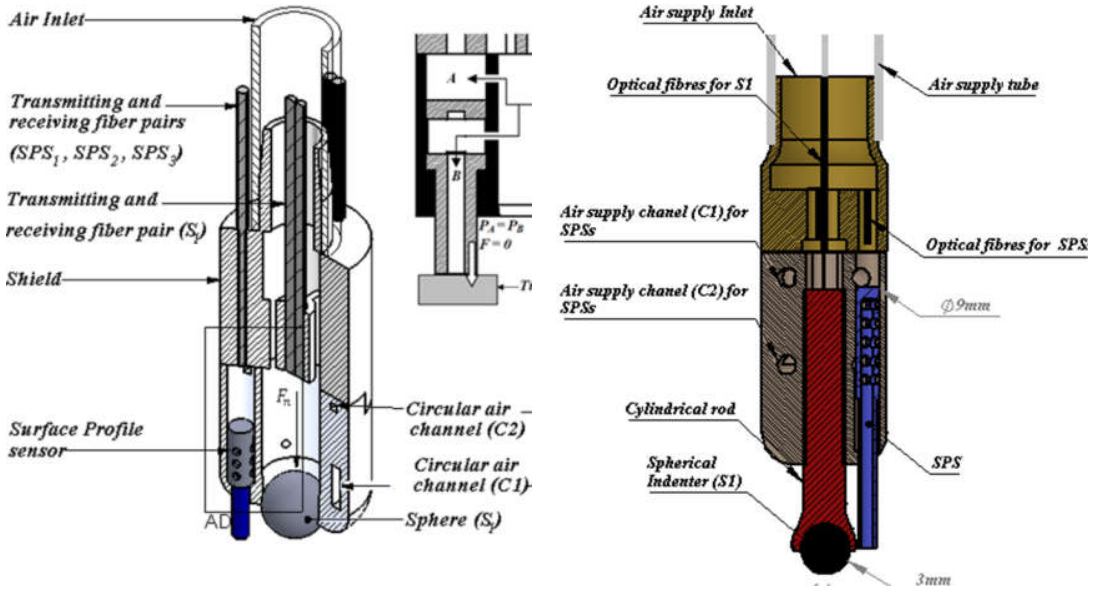

Figure 1. (a) A longitudinal section of the air-float palpation probe indicating the location of fibre optic displacement sensors, SPSs, and Indenter, (b) A longitudinal section of the modified probe.

The new design still retains the feature of the indentation depth sensing mechanism used in the previous design and uses an optical detection circuit with FS-N10MN optical amplifiers combined with 1mm optical fibres in parallel fibre configuration. However, the tip of the indenter is modified to increase the indentation depth and also to improve the sensitivity of the indenter. As illustrated in Figure 1, the spherical indenter is now held at the end of a cylindrical rod. The rod is free to move in axial direction while spherical tip is free to rotate. The length of the cylindrical rod can be adjusted to set the maximum indentation depth expected by the probe. This modification provides a number of advantages including a) the overall diameter of the probe is reduced so that the probe satisfies sizing requirements for MIS surgery b) provides increased indentation depth which improves depth sensitivity of the probe and c) improved tumour localization capabilities due to a smaller indenter providing higher normalized tissue reaction force.

3. Calibration of the new design.

To calibrate the probe for displacement against air pressure, the prototype probe was attached vertically to a single axis linear stage, LTM120 (OWIS), to allow accurate motion control. The inlet of the probe was connected to an electrically controlled pressure regulator, ITV0030 (SMC). The probe was pressurised to extend the indenter and then the linear stage was lowered until only the tip of the indenter was touching the upper surface of a rigid work bench. The linear stage was then programmed, using the motorised position control unit, PS10 (OWIS), to advance towards and retreat from the work surface at a rate of 1mm/s. The process was repeated for a number of cycles and during each cycle, as the indenter gradually pushed in and out of its channel, output of the optical amplifier and output of the pressure sensor were recorded. A 16-bit data acquisition (DAQ) module (NI-USB 6211) and software package

LabviewTM 8.0 were used to acquire voltage signals for air pressure and the optical displacement sensor. The sampling rate was 1000 Hz.

The outcome of the experiment is shown in Figure 2 (a). The blue colour line in this indicates the output voltage of the optical displacement sensor used to track the position of the indenter. The two line segments parallel to the x-axis denote the expected lower and upper bounds of the indenter displacement. The lower bound can be used to control the maximum indentation while the upper bound represents the minimum, or the saturation point of the optical amplifier. Both the upper and lower bounds are adjustable, however, as the range of an optical displacement sensor is always limited to few millimetre, it is important limit the travel of the indentation rod based on the required depth sensitivity of the probe. One other interesting observation of this study is that the voltage output of the pressure regulator (green colour line) remains constant throughout the indentation cycle.

In order to observe this behaviour further, the same experimental procedure was repeated with the previous prototype of the air-float probe. The output of the pressure regulator for both prototypes, for one complete indentation cycle (i.e. advancing and retreat), is shown in Figure 2 (b). According to this, the new prototype maintains a relatively constant air pressure throughout the indentation cycle and therefore, a constant indentation force. In the first prototype, the relationship between the indentation depth and indentation force was nonlinear. During a tissue investigation exercise, as the indenter is pushed back into the probe (due to changing stiffness in the underlying tissue), the displacement of the indenter in the first prototype is opposed by the increasing air pressure. This reduces the sensitivity of the probe. However, in the new design, as the force acting on the indenter remains constant, the displacement of the indenter will be higher. Hence the new prototype possesses a higher sensitivity.

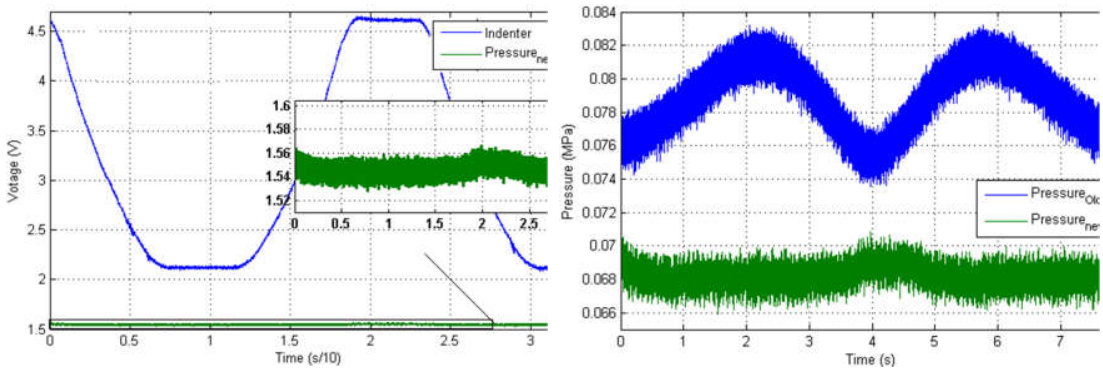

Figure 2. (a) Calibration results for the indenter showing measured voltage and corresponding change in displacement (speed- 1mm/s). The green line shows the supply pressure variations with displacement of the indenter. The change in air-pressure with the displacement of the indenter. (b) a comparison between the new and the previous design of the air-float probe.

4. Tumour Identification Using the Miniaturized Palpation Probe: A Comparative Study

To further investigate the validity of the improvements made to the air-float palpation probe, a comparative study was conducted with both the new and the previous design of the air-float probe. A porcine kidney sample with a spherical tumour (10mm diameter) buried 5mm below the surface (Figure 3) was used to carry out tumour identification tests. A dual axis motorised positioning system (two LTM120) was used during the test to drive each probe across the tissue surface.

During the test, each probe was attached to the positioning system as shown below and lowered until a clearance of 1mm between the probe and the tissue was achieved. Then, output pressure of the electrically controlled pressure regulator was increased gradually until an indentation depth of 3mm is achieved. The manipulator was programmed to follow a path across the tissue and over the tumour. The probe was driven across the tissue, as shown in Figure 3 at a speed of 4mm/s.

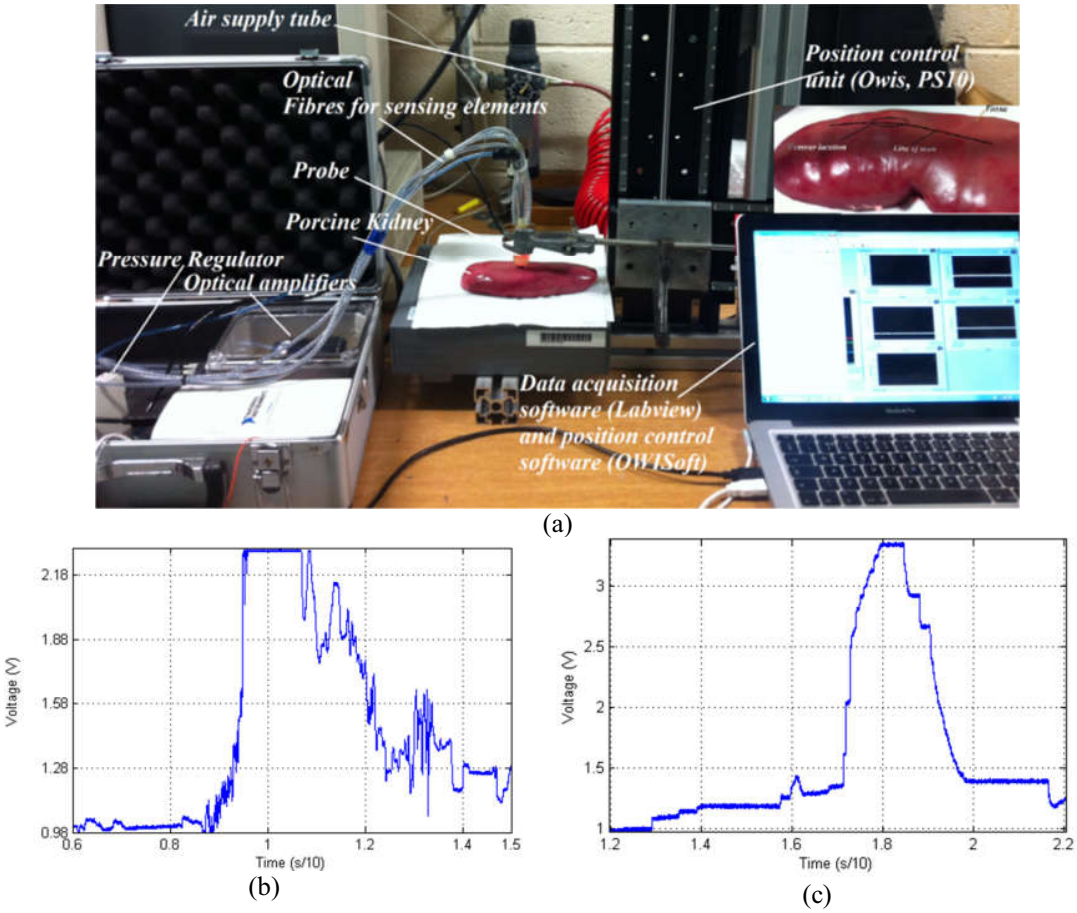

Figure 3. a) Experimental setup used for tumour investigation exercise, b) normalised output of the indenter along the line of scan for the previous prototype, c) normalised output of the indenter along the line of scan for the new prototype.

After each test, data gathered from the optical displacement sensor was used to calculate the normalised voltage of the indenter along the line of scan for both probes. Results are illustrated in Figure 3. From the results shown in Figure 3 (b) and (c), it was clear that both the probes have detected the presence and the location of the tumour. However, the graph in Figure 3(c) is less noisy and the presence of the tumour is more prominent. Further, in this graph, the region of the tumour detected by the indenter is much more close to the actual size of the indenter.

5. Conclusion

In this paper, a modified version of the air-float palpation probe has been presented and verified. The new design is within the sizing requirement for MIS (would fit through standard Trocar port) and can be used to investigate tumours buried deep under the tissue surface. Investigation into the capabilities of the probe revealed that it produces significantly better performance in locating and localising tumours. It is known that the ability to detect tumours decreases exponentially with tumour depth. This can be compensated for by increasing the depth at which indentation tests are carried out. Maximum achievable indentation depth was limited to few millimetres in the previous design due to the restrictions in the

overall size of the probe. However, the proposed new design could overcome this limitation without increasing the overall size of the probe.

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