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A Novel MRI Compatible Air-Cushion Tactile Sensor for Minimally Invasive Surgery

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Abstract—**This paper presents a novel air-cushion tactile sensor for Minimally Invasive Surgery that is fully MRI (Magnetic Resonance Imaging) compatible. The proposed sensor is designed to detect tissue abnormalities within soft tissue surfaces. This is achieved by rolling over soft tissue in a virtually frictionless manner due to the design of the sensor in which the sensing element, a sphere, rests on a cushion of air. This design allows for rapid acquisition of tactile and mechanical properties of large areas of soft tissue. Laboratory experiments are carried out to show its feasibility as a tactile sensor for MIS and its behaviour under loading. The outcomes of the experiments illustrate the sensor's capability and potential as a tactile sensor for MIS. These results are discussed and future work is outlined.**

I. INTRODUCTION

THIS paper summarises a feasibility study of a novel air cushion tactile probe/sensor capable of detecting variations in tissue stiffness during Minimally Invasive Surgery (MIS). These variations in stiffness can be tissue abnormalities such as tumours. The aim of this sensor is to provide tactile feedback to surgeons during MIS which is not readily available due to the limitations of such surgery. The trocar ports restrict the access to the surgical site and the friction of the laparoscopic tools with these distorts the actual tissue contact forces. Other drawbacks of MIS are later discussed in this paper. These drawbacks are more prominent in robotic assisted surgery where tactile feedback is absent on the earlier Zeus Surgical System (Computer Motion, Inc) and the da Vinci Surgical System (Intuitive Surgical, Inc). The benefits of haptic and tactile feedback are discussed at great length in [1].

Providing surgeons with tactile information on the mechanical properties under investigation would allow them to reach well informed decisions on the location and dimension of tissue abnormalities such as tumours; which is readily available during traditional surgery through manual tissue palpation.

Several sensors have been put forward in an attempt to overcome this lack of tactile feedback. The proposed sensor makes use of an air-cushion force sensing probe comprised of a spherical end effector resting on a pressurised air cushion. The design of the sensor makes it also fully MRI (Magnetic Resonance Imaging) compatible which is a rare feature. Two experiments are presented in this paper, the first one is aimed at establishing the behaviour of the sensor under loading conditions and the second is aimed at establishing its feasibility as a tactile sensor for MIS.

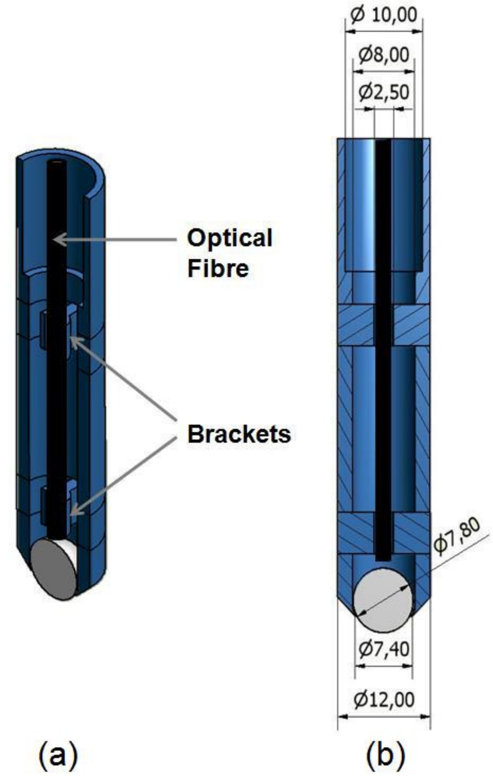

Fig.1. A three dimensional cross-sectional drawing of the proposed air-cushion tactile probe with the supporting brackets is shown in (a). The dimensions of the sensor are illustrated in (b) with all the measurements being in millimeters.

II. BACKGROUND

A. *Minimally Invasive Surgery*

The term Minimally Invasive Surgery (MIS) refers to a form of surgery that is performed through small incisions. The size of these incisions varies between 3-12mm in diameter [2]. They are strategically located around the surgical site so as to offer the best access. A camera is initially inserted through one of the incisions so as to offer a field of view of the surgical site. Laparoscopic tools are then

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inserted through these incisions to perform tissue investigation, dissection, suturing or manipulation.

Compared to traditional surgery, MIS offers distinct benefits such as a reduction in post operative analgesic requirements, length of hospitalisation, blood loss, rehabilitation time and improved aesthetics. Unfortunately MIS does suffer from some significant drawbacks [3] such as a lack of tactile and haptic feedback. In traditional surgery, surgical tissue palpation takes place with the surgeon's hand to establish the tissue properties and abnormalities such as tumours; this is not possible in MIS as the access to the surgical site is limited due to the size of the incisions. Another problem is the friction between the surgical tools and the laparoscopic trocar ports which greatly distorts the actual tissue contact forces of the tool tips preventing any possibility in sensing the reaction forces through the tool shafts. Moreover, the trocar port restricts the tool's movement to four degrees-of-freedom (pitch, yaw, roll and insertion) resulting in the loss of hand eye coordination [4] due to the fulcrum effects which reverses the directions of the tools at their tip.

A. *Minimally Invasive Robotic Surgery (MIRS)*

Over the past decade, several surgical robotic devices have been developed in an attempt to tackle the drawbacks associated with MIS. The most popular robots are the Zeus Surgical System (which is no longer marketed) from Computer Motion, Inc [5] and the da Vinci Surgical System from Intuitive Surgical, Inc [6]. Both surgical systems make use of a master-slave concept where the master is a surgical console controlled by the surgeon and the slave is a tele-operated cart with three or four robotic arms [7,5]. The main benefits of surgical systems are the three dimensional field of view (with depth perception), their ability in scaling down hand movements due to the improved distal dexterity and the removal of the fulcrum effect allowing for complex surgical procedure that would otherwise be difficult in traditional MIS such as coronary bypass grafting [8] and mitral valve repair [9]. Despite these improvements none of these surgical systems offer any high quality haptic feedback which is a major concern. The need for tactile and haptic feedback is even more important when the camera's field of view is compromised by fluids or other residues.

B. *Force and Tactile Sensors for MIS*

There are a number of feedback principles that can be required during surgery, these are visual feedback, tactile (cutaneous) feedback and force (kinaesthetic) feedback. Haptics illustrates both cutaneous and kinaesthetic information which are both needed to mimic the sensation felt by a human hand [10]. This sense of feel is critical for performing suturing, manipulation and tissue palpations in any type of surgery such as traditional surgery, MIS and MIRS. Several sensors have been designed over the past years in an attempt to overcome this lack of haptic feedback in MIS. These sensors can be positioned in four different locations on the laparoscopic tools [1]. The sensing element can be located close to the actuation mechanism consequently measuring the stress by the actuation mechanism. This location suffers from backlash, inertia, gravity and friction as it is far away from the surgical site [1]. The second position is on the shaft of the laparoscopic tool, outside the patient's body. The benefit of this location is that there are few constraints concerning the material and size of the sensor. The drawback being that it can be affect by the friction and reaction forces of the trocar port. The third location would be on the shaft inside the patient's body which would not suffer from the forces exerted at the trocar port but would be constrained by its size. The final location would be the tip of the laparoscopic tool as it is in direct contact with the tissues. The advantage of such a location is that the sensing element is not affected by surrounding forces but it has to be of a very small size. Several sensing methods are used for MIS: current based, resistive-based, capacity based, pressure based, optical based, piezoelectric based, vibration based and displacement based sensing [1].

The literature on such sensors is extensive so only a select few are mentioned for illustration purposes. Bicchi et al. make use of strain gauges to discriminate between objects of different stiffness [2]. Schostek et al. suggest a low cost force sensor array that measures the force distribution over its area and is incorporated inside the jaws of a laparoscopic grasper [11]. Peine et al propose palpation instrument for artery localisation in MIS [12]. This sensor has a capacitive tactile array as a sensing element which is located at the tip of a laparoscopic instrument and is pressed against the issue under inspection. This sensing array made of crossed copper strips and silicone rubber spacers can measure the magnitude of the force and its distribution across the area. Using the indentation principle, McCreery et al [13] designed a laparoscopic probe with an in-built force/torque sensor. Similarly Noonan et al [7] designed a rolling indentation probe which is considered to be more effective in acquiring stiffness distribution information since continuous rapid movement can be performed. In contrast to the aforementioned sensors, the proposed tactile sensor is designed to achieve near-frictionless rolling by having a "floating" cushion of air. Its manoeuvrability is greater than the wheelbase sensor [14, 15] which has shown its potential in a medical environment, as it is not constrained to movements normal to the longitudinal axis. The proposed tactile air cushion probe can move in any direction on the spot along the sample tissue surface.

III. DESIGN OF AIR CUSHION TACTILE PROBE

A. *Structure and Principle*

The proposed sensor is designed to be used as a tactile probe for MIS. The sensor consists of a shaft of outer diameter 12mm (see Fig.1b), which is within the acceptable MIS standard. The inner walls of the shaft have a diameter of 8mm which increases to 10mm at the distal end and narrows down to 7.4mm at the tip of the shaft. A 7.8mm in diameter sphere is located at the tip of the shaft. Two brackets (see Fig.1a) are placed above each other at distance of 25mm from one another inside the shaft walls. The brackets have an inner diameter of 2.5 mm and are designed to support an optical fibre that is placed just above the sphere, this is illustrated in Fig.1a. The optical fibre has an outer jacket of 2.2mm and a core of 1mm. The length of the shaft is 60mm long. The structure of the sensor and the sphere are made out of ABS plastic and were built using the three dimensional rapid prototyping machine Dimension 768. The distal end of the sensor is connected to a compressor and the optical fibre is connected to an electrical circuit.

The motion of the sphere along the longitudinal axis of the shaft is detected by the optical fibre. The optical fibre is the one end of a 1 x 2 optical coupler with 50:50 ratios (Industrial Fiber Optics, Inc., AZ, USA); which is connected to an optical scheme comprising a superbright LED as a light source and a photosensitive detector. The optical fibre inside the shaft both emits and collects the light generated by the optical scheme and reflected off the sphere (see Fig.2). As the distance between the tip of the optical fibre and the sphere changes; so does the light intensity collected by the fibre. This scenario is illustrated in Fig.2, initially the sensor is rolled over a flat tissue surface maintaining a distance d1 between the sphere and the tip of the optical fibre (see Fig.2a.) and subsequently when it encounter a change in the mechanical properties of the tissue the distance between the tip of the optical fibre and the sphere is reduced to a distance d2 (see Fig.2b.). This change in light intensity is reflected by a variation in voltage readings of the optical scheme. The voltage variations are collected using a data acquisition card attached to a computer.

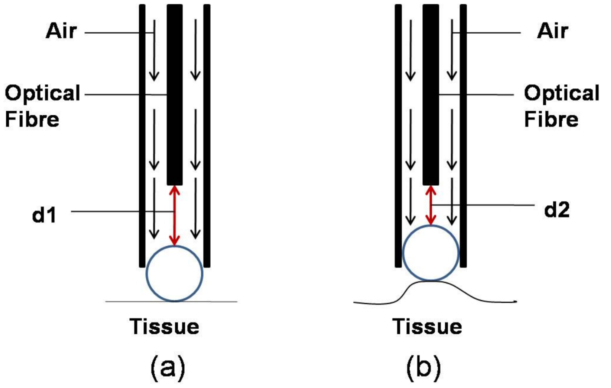

Fig.2. A schematic explaining the working principle of the optical scheme. In (a) the distance between the sphere and the optical fibre is d1, it is reduced to d2 when the sensor is rolled over a tissue abnormality (b).

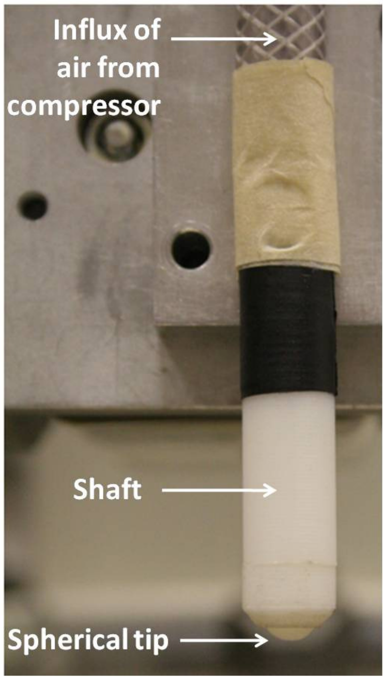

Fig.3. A picture illustrating the novel sensor attached to the robotic manipulator and connected to the compressor through an air tight tube.

The distal end of the probe is connected to compressor (see Fig.3) that generates a steady flow of air which applies pressure onto the sphere. As the sphere is rolled over the tissue and pushed along the longitudinal axis of the shaft; it rolls on a cushion of air generating a near frictionless roll. As the distance between the shaft and the tissue under inspection are kept constant; the displacement of the sphere along the longitudinal axis of the shaft indicates a change in the mechanical properties of the surface. This method allows for rapid acquisition of tactile maps of a tissue under inspection.

IV. EXPERIMENT 1

A. *Sensor's Behaviour under Loading Conditions*

The first experiment carried out was to establish the sensor behaviour under loading conditions. The experimental setup consisted of attaching the sensor to the distal tip of a Mitsubishi RV-6SL 6-DOF robotic manipulator. The sensor was positioned onto a scale with only the tip of the sphere touching the scale. The overall schematic of the experimental set-up is displayed in Fig.

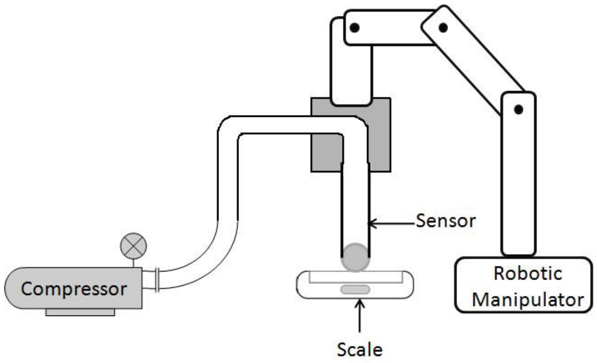

Fig.4. A schematic of the experimental setup for the sensor's behaviour under loading experiment.

4. The scale used for the experiment had a resolution of 0.02 grams. The weight of the sphere with the compressor turned off was observed to be 0.20 grams. For the experiment the compressor was turned on to generate a constant flow of air. During the experiment the sphere was gradually indented (0.1mm at a time) into the shaft by lowering the sensor onto the scale. The readings of the weight generated for each indentation were taken. The initial position of the sphere was taken when it is fully extended at the tip of the probe and its indentation was measured from that point. The maximum indentation achieved was 1.3mm. This experiment was carried for three different pressure readings given by the compressor. These were 1psi, 2psi and 4 psi which are equivalent to 6.9kPa, 13.8kPa and 27.6kPa, respectively.

B. *Results*

The results obtained were converted into Newtons and were then plotted against the indentation depth which can be seen in Fig. 5. It can be noted that for all three pressures the force of the probe drops as soon as the sphere is indented into the shaft. It can be observed that for the pressures of 6.9kPa and 13.8kPA the force remains relatively constant for indentations ranging from 0.3mm to 1mm. For the pressure of 27.6kPa the force stabilises itself from an indentation of 0.7mm to 1.1mm. The force exerted by the sphere increases for indentations from 1.2mm to 1.4mm regardless of the pressure. The reason for this is that as sphere is indented into the shaft more air escapes exerting an additional force onto the surface. Despite this change in behaviour for indentations greater of 1.2mm the force exerted is never greater than the initial force. This has to be noted as it is of great importance. This enables us to know that when an initial force is set (as it is related to the pressure generated by the compressor) it will never be exceeded regardless of the indentation. This prevents the sensor from exerting any force that may damage the tissue as long as the initial force is set according to the tissue's limitations. Further work will have to be carried out to establish the mathematical modelling between the pressure of the air generated by the compressor, the force exerted onto the tissue and the coefficient of elasticity of the surface under inspection. However, at this stage in the development of this new sensor, we have an approximate idea of the behaviour of the sensor when it is loaded.

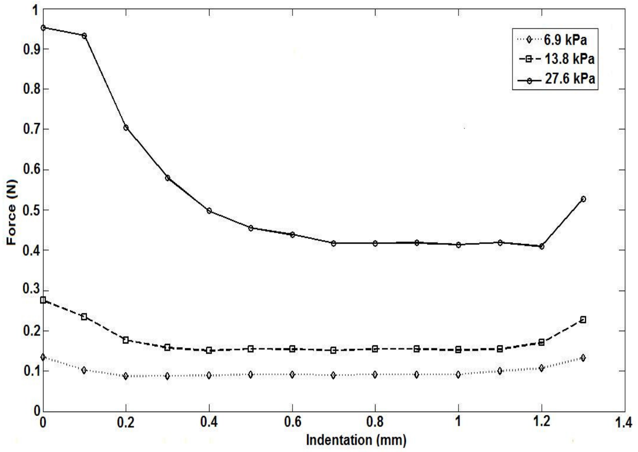

Fig.5. A plot of the force (N) exerted by the sphere against the indentation (mm) of the sphere into the shaft for three different pressures: 6.9kPa, 13.8kPa and 27.6kPa.

V. EXPERIMENT 2

A. *Silicone Rollover*

This experiment was carried out to establish the feasibility of this novel air cushion probe as a tactile sensor for MIS. The sensor was attached to the distal tip of the

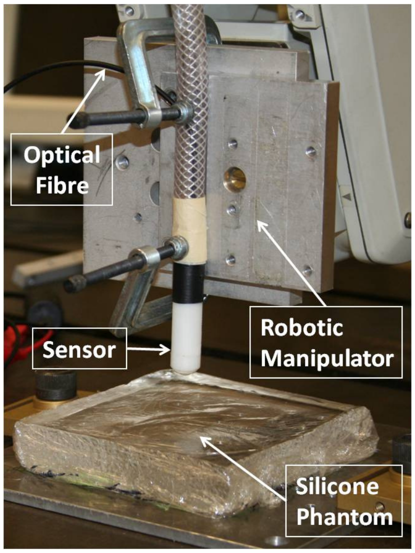

Fig.6. The experimental set-up of the silicone rollover experiment displaying the silicone phantom, the sensor attached to the robotic manipulator and the optical fibre that is hermetically inserted into the sensor through the tube that is connected to the compressor.

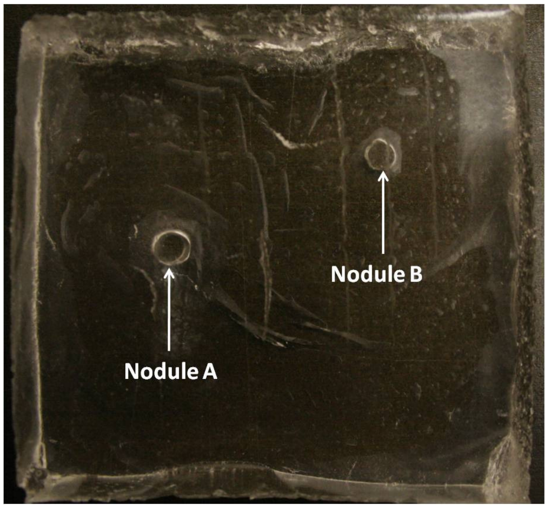

Fig.7. Nodule A and nodule B covered with the silicone phantom to generate ‘abnormalities’.

Mitsubishi RV-6SL 6-DOF robotic manipulator to achieve controlled movement over the surface under inspection. Data from the optical scheme was collected using a data acquisition card and the National Instrument LabView 8.0 software package associated with it. The surface that the sensor was rolled over was a silicone phantom of dimensions 100mm x 100mm and thickness 20mm. The experimental set up is illustrated in Fig.6. The silicone phantom does not contain any nodules so these had to be placed under it which is shown in Fig.7. The two nodules used were made from a similar silicone mix to the one used for the phantom. This was done to make the task of detecting the nodules more difficult as they had a similar elasticity. This resembles more an in vivo environment where the tumours are also elastic. Nodule A and nodule B were of cylindrical shapes with heights of 6mm and 2mm respectively and diameter 5mm. The nodules are illustrated in Fig.8 next to a one Pound Sterling coin. The nodules were positioned vertically under the silicone phantom just as they are displayed in Fig.8.

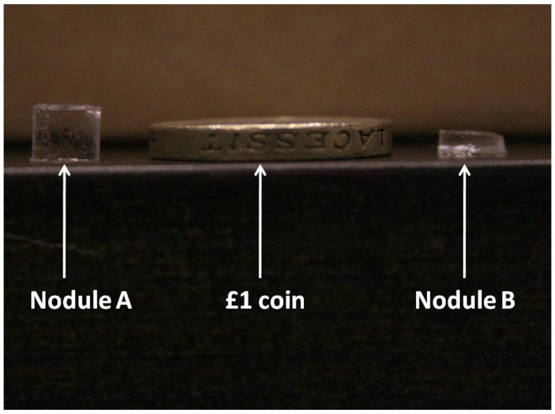

Fig.8. Nodule A and Nodule B next to a Pound Sterling coin.

At the start of the experiment the compressor was set to generate a pressure of 6.9kPa, creating a constant air flow. The sphere was rolled over the silicone block in 8 parallel and adjacent rolls to cover the area under which the nodules were buried. For each roll data was collected based on the readings of the optical fibre which is affected by the motion of the sphere along the longitudinal axis of the shaft. The speed at which the rolls were carried out was kept constant. The indentation depth of the sensor onto the silicone phantom was set to 1.5mm.

B. Results

All of the 8 parallel rolls generated data from the optical fibre. This data was used to create a three dimensional map of the silicone block which is illustrated in Fig.9. The nodule A can clearly be identified where as nodule B is a bit more discreet. The red colour indicates the highest stiffness area where as the yellow area indicates an area of lesser stiffness and with the blue colour indicating an area of low stiffness. The reason for which the nodule A is surrounded by a vast yellow area is that its height of 6mm raises the

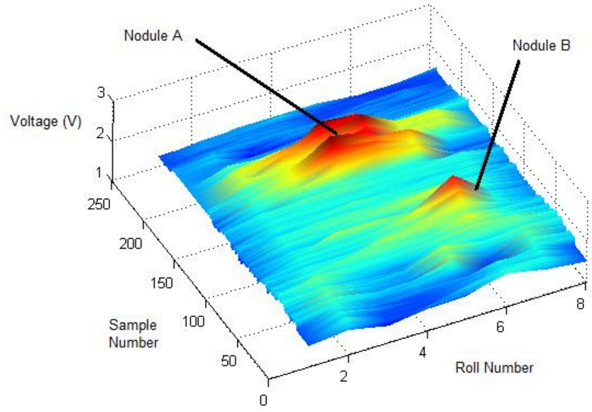

Fig.9. A three dimensional plot of the silicone block illustrating the positions of nodule A and nodule B.

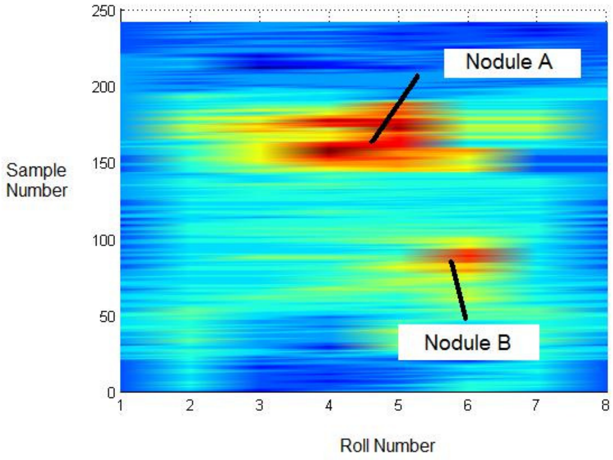

Fig.10. The top view of the three dimensional plot of the silicone block with Nodule A and Nodule B.

surrounding area of the top of the nodules consequently raising the silicone phantom from underneath. The same phenomenon happens with Nodule B but this is less visible as it has a height of 2mm. A top view of the three dimensional plot is shown in Fig.10. The two nodules are visible with the top of the nodules shaded in red and the surrounding area in yellow.

VI. DISCUSSION

The results achieved in both experiments are encouraging. The first experiment illustrated the sensor's behaviour when the sphere is indented into the shaft. This experiment showed how the force exerted by the sensor is altered when the sphere is moved in the longitudinal axis of the shaft and the air flow kept constant. The results of this experiment showed that the force exerted by the sensor is at its maximum when the sphere is fully extended at the tip of the shaft. This finding is reassuring with the knowledge that if the force is set correctly when the sphere is fully extended, no motion of the ball will increase the force of the sensor hence not damaging any tissue under inspection.

The second experiment approximated the behaviour of the sensor when rolled over animal tissue at least to a certain extent. It was impressive to see that nodule B with a thickness of just 2mm was detected under a silicone phantom of 20mm. It is even more remarkable as the nodule was made of similar material as the silicone phantom.

VII. CONCLUSION AND FUTURE WORK

This paper presents the feasibility study of this novel tactile sensor for MIS. The suggested sensor makes use of an air cushion on which the sensing element, a sphere, "floats" when it is rolled in a near frictionless manner over a tissue under inspection. The sensor examines the mechanical properties of the tissue by generating a tactile map of the area illustrating the zones with different tissue stiffness. The current design, being a sphere, can follow straight and curved paths making it ideal to examine complex surfaces with ease. This design has shown its potential as a tactile sensor during the silicone experiment. This design is also remarkable as it is entirely Magnetic Resonance Imaging (MRI) compatible. The all plastic design and the use of an optical fibre are not affected and do not disturb magnetic fields during the MRI process. This design could therefore be used live in conjunction with MRI during MIS.

Future work will focus on carrying out ex-vivo trials with animal tissue and eventually move onto human tissue following hospital ethical committee approval. There is also a need to mathematically model the behaviour of the sensor in relation to the flow rate of air, the force generated and the coefficient of elasticity of the surface.

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