Disposable Stiffness Sensor for Endoscopic Examination

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***Abstract*— Since direct manual palpation is not possible in minimally invasive surgery procedures, there is an active field of applied research which aims to retrieve the human sense of touch and feedback tissue properties through artificial tactile feedback. This paper presents an innovative stiffness sensor to be embedded at the tip of a commercial endoscopic camera. The sensor structure is based on multiple cantilever beams, which act as springs with different stiffness when indented into soft tissue. Geometric features mounted on the beams are tracked during physical contact. Movements of the cantilevers result in shape variations of the features in the camera images. The feature size is then segmented and related to the force exerted into the contact location. As beams of different elasticity are integrated, it is possible to estimate the stiffness properties of the soft tissue by employing only visual information. In this paper, Finite Element Analysis (FEA) was implemented to simulate and estimate how contact forces will affect the material and design of the prototype. A calibration device has been developed and used to validate the outcome of the FEA simulations. An experimental test showed the ability of the proposed mechanism to compute the stiffness of a soft phantom.**

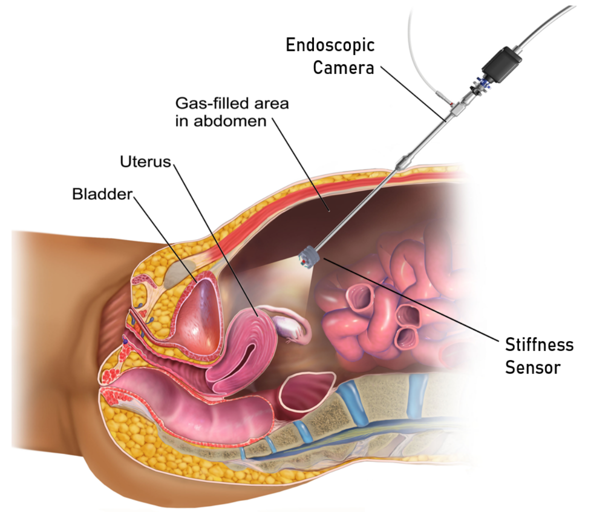

Fig. 1. Stiffness Sensor mounted at the tip of an Endoscopic Camera. Image modified from source: Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436, by BruceBlau.

I. Introduction

Minimally invasive procedures have proven to have great advantages for the patient, which derive mainly from accelerated healing of the small access wounds [1]. Thus, over the past few decades, less invasive procedures are being used as the best choice, compared to traditional treatment, for medical diagnosis, surgical operations and many challenging medical practices [2]. However, in open procedures, clinicians have a direct view of the anatomical areas and can perceive tissue features with the gloved hand, which is a minimal restriction of tactile perception. It has been proven that stiffness variation of anatomical surfaces provides important information in recognising abnormal tissues, blood vessels, ureters, as wel as bones and fatty tissue. On the contrary, in minimally invasive procedure, in which long and thin instruments are inserted into natural orifices or trocar ports, hand-eye coordination is required to manipulate special instrumentations and the tactile sensations are completely lost. Moreover, force applied to soft organs can only be estimated through visual feedback by observing the deformation of the tissue in the transmitted camera images [3]. Thus, the lack of direct palpation during minimally invasive procedures may lead to accidental tissue damage or to insufficient feedback of tumour excising. Several researchers have studied the use of commercial sensors for minimally invasive procedures, but, as the use of instruments in surgical robots is usually limited to 10-15 times, the price of these devices represents a big limitation [4]. Moreover, the size of commercial sensors is considerably larger than the general diameter of a trocar port [5]. In addition, another trocar port is required to integrate these sensors in the surgical setup [6]. Hence, the developing of a low-cost disposable device for tissue stiffness characterisation in minimally invasive procedures is highly demanded [7].

In previous work we developed a vision-based single axis force sensor device for MIS [8]. The sensory mechanism evaluates the contact force by tracking the visual appearance of a sphere in camera images, which is correlated to the compression of a spring. The derived sensing principle has then been adapted in the vision-based stiffness sensor for surgical endoscopic camera presented in [9]. Two springs of different elasticity have been embedded in this sensor. The interaction with external surfaces, generates two different reaction forces from which the stiffness of the contact surface is derived. Experimental results shown that the sensor presents high accuracy, however, the computation of the stiffness is sensitive to the contact angle. In order to increase the robustness of the proposed sensing methodology, we

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developed a multi-directional stiffness sensor for external palpation [10]. In this paper, we present a novel tactile structure in which the elastic movements produced by the springs has been replaced with the deflection of elastic cantilever beams reducing the sensor's size significantly. The new design makes the sensor lighter and easy to be embedded into a commercial endoscopic camera as shown in Figure 1. The addition of the proposed sensor enhances the functionality of the endoscopic camera which becomes a dual sensor used for visualisation but also as diagnostic instrument. The advantages of this sensing device are:

- The clip-on stiffness sensor is passive and can be fabricated at low-cost.
- The adaptation of the proposed sensor in minimally invasive application does not require any additional trocar port as it is supposed to be attached to the endoscopic camera which is commonly used during the medical procedure for visualising the anatomical areas.
- The fabrication material and design can be customised, enabling its range and accuracy to be tailored according to the desired application.

II. Mechanical sensor structure

The stiffness sensor has been fashioned for the medical rigid endoscope ENDO-CAM Performance HD by Richard Wolf GmbH (30 fps at 60 Hz). The sensor is attached to the tip of the endoscopic camera by a clip so as to be easy to fasten or removed. The overall sensory system, composed by the endoscopic camera and the designed mechanism, can be inserted into the human body through a standard trocar port of $10-15mm$ diameter, thus it fits the size requirements of minimally invasive procedures. Moreover, the sensor's design can be tailored in order to fit the size requirements of a generic endoscopic camera presenting different dimensions. The sensors range depend on the design, i.e. the dimensions of the beams and the mechanical properties of the material used to fabricate it. The design has been developed in SolidWorks 2016, a CAD software for 3D modelling. The sensor consists of two semi-cylindrical symmetrical parts with a cylindrical cavity along the central axis which is used to mount the device onto the camera tip. Each part has two cantilever beams with an indenter and a geometric feature as shown in Figure 2. During the interaction with soft tissue, forces are exerted on the indenters and the cantilever beams are bent towards the camera axis. This results in a changing of size and position of the visual features in the camera image. Three beams have identical cross sections, hence they have identical elastic constants. This set can be used to calculate the plane characterizing the contact surface. Further, the barycentric displacement of the plane can be combined with the displacement of the other beam, which has a bigger cross section and thus a lower elasticity, to evaluate the stiffness of the tissue [10].

III. Methodology

Finite element analysis has been performed using Abaqus 6.14. This study allowed to evaluate the relation between the force and the displacement as well as the relation between the stress and displacement that the cantilever exhibits when subject to a normal force. The FEA results have been compared with the results obtained using a calibration device. The following sections present this process in detail.

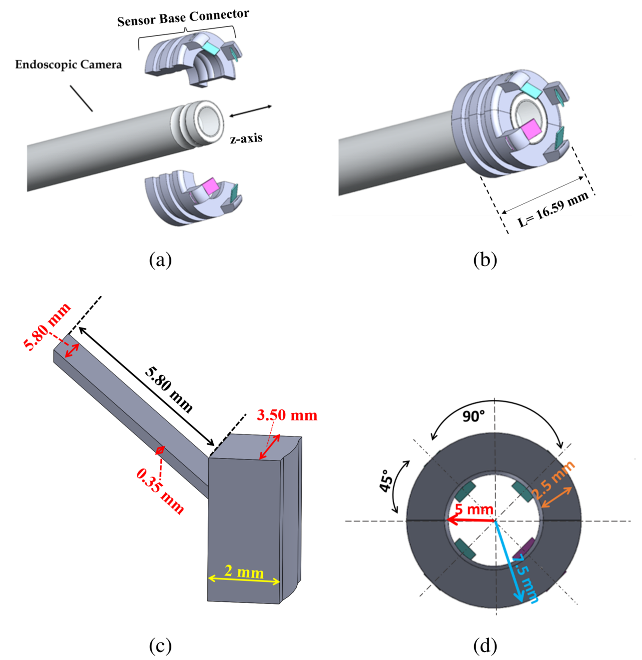

Fig. 2. CAD Drawing: (a) Exploded view of the prototype. (b) Sensor assembled a the tip of an endoscopic camera. (c) Specification of the cantilever. (d) Camera field of view.

A. Finite Element Analysis

The FEA analysis consists of three main stages: the pre-processing, which involves the creation of the file to input for the analysis, the processing, which produces the output visual file and the post-processing which generate the report and data from the output file. In the pre-processing phase we imported the parts created in SolidWorks and defined the material properties. The material used in the simulations is Nitinol, a metal alloy of nickel and titanium with a Young Modulus of 40 Gpa. The material properties have been extracted from the material data sheet of the rapid prototyping machine used to fabricate it. As the sensor is supposed to be printed using the same material, the model has been assigned with homogeneous solid section. In the boundary conditions, the bottom part of the beam, which is supposed to be attached to the sensor base connector, has been defined as fixed. The maximum force applied to a tissue or organ is less than $1N$ during most medical tasks. Accordingly, a concentrated force of $1N$ has been applied at the tip of each beam, which is supposed to indent the soft surface. The accuracy of the simulation depends on the size of the seeds used in the mesh generation, e.g. with small seeds the simulation results are more accurate, however, if the seeds are too small the computation time will increase dramatically and cause failure of the analysis. To achieve a balance between accuracy and computation time, in meshing

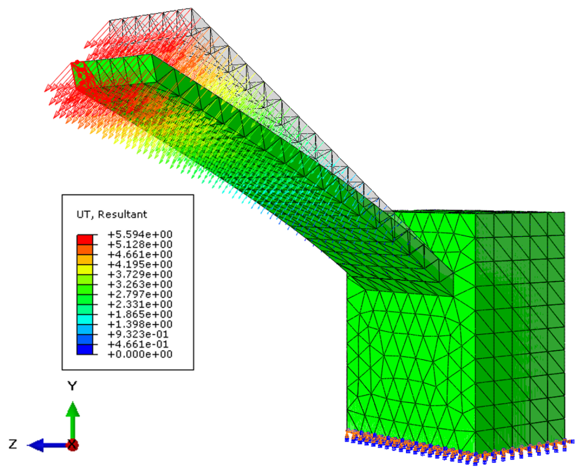

Fig. 3. FEA results showing the mesh, the boundary conditions and the displacement of the cantilever due to a normal force.

the part we choose seeds of $0.4mm$. The visualization of the FEA results for one of the cantilever is shown in Figure 3.

B. Calibration setup

A calibration device which ensures that the endoscopic camera is at a steady state during contact, has been developed. The system employs a motorised linear module which embeds the ATI Nano 17 Force/Torque sensor, as shown in Figure 4. By sliding the linear module, and thus the Force/Torque sensor, against the sensor prototype, the displacements of the beams and the interaction forces generated by the contact are recorded in real-time. When normal forces act on the tip sensor, the beams will move and bend. The movements of each beam in the three dimensional space are related to the movements of the centroid associated to the corresponding visual feature in the camera images.

IV. Evaluation tests

The tests have been executed on an Intel i5 processor running at 2.8 GHz. In order to compare the results of the FEA with the calibration test, the calibration device has been used to evaluate the response of each single beam to

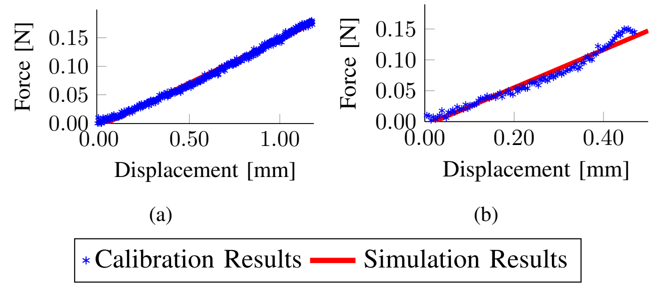

Fig. 5. Stiffness sensor for endoscopic camera: Evaluation Results. Displacements of the nitinol beams along the vertical axis in simulation and calibration of the soft beam (a) and the stiffer (b).

an applied force. The comparison between simulation and calibration results are shown in Figure 5. Both, the soft and the stiffer beams, bend consistently even when the applied normal force is small. The elasticity of the soft beam is twice as high as the elasticity of the stiffer beam. Beside, the sensor range and resolution can be customised by changing the dimension of the cantilever or using material with different Young Modulus, i.e. different elasticity.

A. Tracking of the cantilever beams

The image processing algorithm evaluates the relationship between the bending of the cantilevers and their visual appearance in the images. The image has been subdivided into four Regions of Interest (ROIs), as shown in Figure 6, where the tracking of each beam is performed.

The results of the calibration demonstrate that the relationship between the displacement of the nitinol beams and the applied normal force is linear (Figure 5). The results of the image processing algorithm also show that there is a linear relationship between the position of the centroids in the image and the displacements of the beams, Figure 7. The correlation between the positions of the centroids in the images and the bending of the corresponding beams allows to directly link the movement of the centroids to a contact force. For instance, if a normal force of $0.1N$ is applied at the tip of the soft beam, this will bent of $0.6mm$, Figure 5 (a). Consequently, the relative centroid will exhibit a variation of 10 pixels in the images, Figure 7(a).

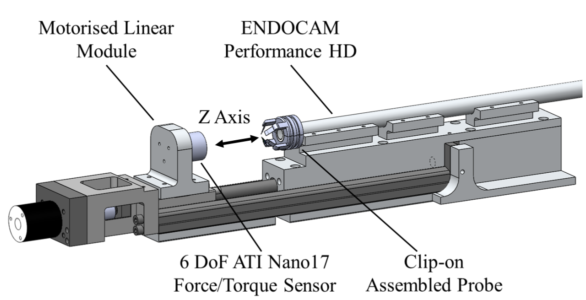

Fig. 4. Calibration device: The motorised linear module pushes the ATI Nano 17 Force/Torque sensor against the stiffness sensor whist recording the interaction forces and the displacement.

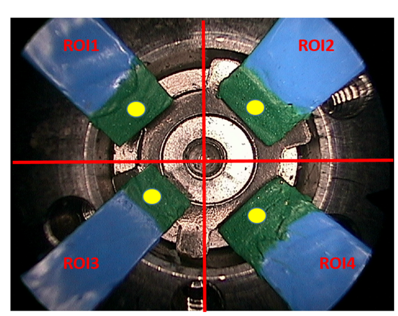

Fig. 6. Image processing algorithm: Position of the beams in the image at the maximum displacement (indentation of $2.5mm$).

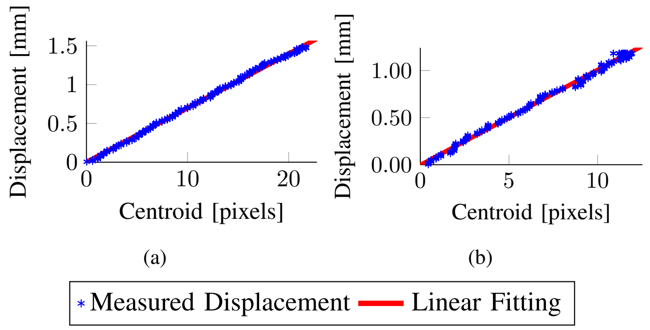

Fig. 7. Image processing algorithm: Relation between tracked feature centroid and displacement of the soft beam (a) and stiffer beam (b).

B. Stiffness Computation of Soft Phantom

A soft phantom with a stiffness of $0.0854N/mm$ has been used to evaluate the ability of the proposed sensor in computing the stiffness of soft material. The stiffness of the phantom has been computed experimentally by employing a device with the same geometry of the developed stiffness sensor and a commercial Force/Torque sensor. During the tests the stiffness sensor has been linearly pushed against the soft phantom, while the visual appearance of the beam was used to track the centroid of the correspondent visual features in real time. Figure 8 shows the experimental setup. The image processing algorithm enabled to evaluate the forces generated by the interaction of the beam with the external surfaces. The difference in force was then used to evaluate the stiffness of the contact surface, K, [9]:

$$K = \frac{(K_{b1}\Delta x_{b1} - K_{b2}\Delta x_{b2})}{\Delta db} \quad (1)$$

where the $K_{b1} = 0.15N/mm$ represent the stiffness of the soft beam and $K_{b2} = 0.25N/mm$ is the one associated to the stiffer beam. The stiffness of the cantilever, which is the slope of the line in the in the Force/Displacement space, have been evaluated experimentally, i.e. each beam have been linearly pushed against the benchmarking force sensor. The displacement of the soft and stiff beams, $\Delta x_{b1} = 0.8mm$ and $\Delta x_{b2} = 0.3mm$ have been derived from the image processing algorithm by employing the linear relation between the displacement of the beam and the movements of the centroids in the images, Figure 7. In Equation 1

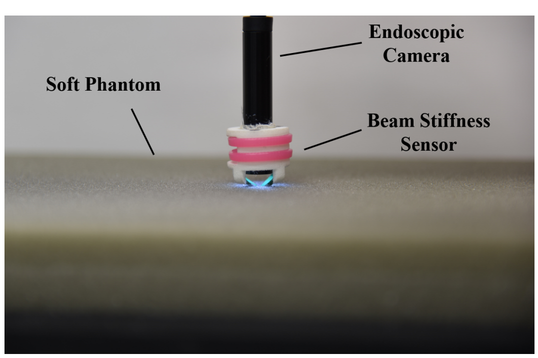

Fig. 8. Stiffness Computation of Soft Phantom: Experimental Setup.

$\Delta db = 0.5mm$ represents the difference in displacement between the centroids associated to the two beams. Hence, the value of the stiffness of the soft phantom, K, computed by the developed device, results to be $0.09N/mm$. Thus, the error in the estimation of the stiffness is 5.3864%.

V. Conclusion

In this paper a novel clip-on stiffness sensor for endoscopic camera has been presented. The proposed mechanism is light, cheap, disposable, passive and easy to integrate on the tip of a surgical endoscopic camera. The sensory system employs cantilever beams which are used to palpate soft tissues. The sensing principle relies on an image processing algorithm to compute the reaction forces which are used for soft tissue stiffness estimation. Finite element analysis has been performed to evaluate the response of the cantilever to normal forces. Simulation tests have been validated with a calibration device. Results shown a linear trend of the cantilever for the range of force required by the targeting application. Moreover, experimental tests showed a linear relation between the visual features in the images and the displacements of the beam during the examination. Future work will investigate the optimality of the design, implementation of robust tracking algorithm, more evaluation on the multi-directional capability of the device as well as in-vivo tests.

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