World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:3, No:6, 2009

Design, Modeling and Fabrication of a Tactile Sensor and Display System for Application in Laparoscopic Surgery

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***Abstract*—**One of the major disadvantages of the minimally invasive surgery (MIS) is the lack of tactile feedback to the surgeon. In order to identify and avoid any damage to the grasped complex tissue by endoscopic graspers, it is important to measure the local softness of tissue during MIS. One way to display the measured softness to the surgeon is a graphical method. In this paper, a new tactile sensor has been reported. The tactile sensor consists of an array of four softness sensors, which are integrated into the jaws of a modified commercial endoscopic grasper. Each individual softness sensor consists of two piezoelectric polymer Polyvinylidene Fluoride (PVDF) films, which are positioned below a rigid and a compliant cylinder. The compliant cylinder is fabricated using a micro molding technique. The combination of output voltages from PVDF films is used to determine the softness of the grasped object. The theoretical analysis of the sensor is also presented.

A method has been developed with the aim of reproducing the tactile softness to the surgeon by using a graphical method. In this approach, the proposed system, including the interfacing and the data acquisition card, receives signals from the array of softness sensors. After the signals are processed, the tactile information is displayed by means of a color coding method. It is shown that the degrees of softness of the grasped objects/tissues can be visually differentiated and displayed on a monitor.

***Keywords*—**Minimally invasive surgery, Robotic surgery, Sensor, Softness, Tactile.

I. Introduction

MIS is a technique developed to decrease the traumatic effects of various types of open surgeries.

Endoscopic and laparoscopic surgeries are among the most popular kinds of MIS [1]-[5]. Unlike open surgeries, in this type of operation, the surgeons do not have their hands inside the patient's body [6]-[9]. As a result, different medical manipulations are conducted outside the operative zone. In other words, by using long slender instruments, these manipulations are transmitted to the operative site.

The advancement of MIS techniques is also helpful for the development of Robotic Assisted Minimally Invasive Surgery as well as Tele-Robotic Minimally Invasive Surgery and in general for the tele-operation procedures. MIS is one kind of tele-operation. In MIS, the hands of the surgeon are not at the site of the operation. Consequently, minimally invasive tools can be integrated usefully into tele-operation systems.

MIS has a considerable number of advantages, such as, less tissue damage, less postoperative pain, faster recovery period, fewer postoperative complications, and reduced hospital stay. It also suffers from several disadvantages [10]-[13]. These disadvantages include: loss of tactile sensing feedback, the need for increased technical expertise, a possibly longer duration of the surgery, and difficult removal of bulky organs. Among these problems, the loss of tactile sensing has proven to be the most serious issue. It has been the target of extensive research [14]. Much research about restoring the sense of touch to the surgeon has been performed [15]-[17]. In order to improve the manipulation ability of endoscopes, a new tactile sensor system using image processing has been developed [18]. This system uses an infrared (IR) cut pattern. It is possible and easy to install the sensor in the tip of an existing endoscope. In a research work, by using a modified commercial endoscopic tool, the magnitude of the applied force was measured by strain gauges. Then the position of the grasper was determined with an optical detector [15]. The researchers obtained force-displacement data, using which they identified objects with five different elastic properties. The development of an active haptic sensor for monitoring skin conditions has been discussed [19]. The base of this tactile sensor is an aluminum cylinder, around which a poly-urethane rubber layer, a PVDF film, a protective surface layer of an acetate film, and lace are stacked in sequence. Their experimental results showed that the sensor system works well as a haptic sensor for monitoring skin conditions. A study has been published that discusses basic design parameters used for the production of tactile elements using electro-rheological fluids [20]. The final aim was to produce a prototype three-dimensional tactile display comprising electrically switchable micro-machined cells of which the mechanical moduli are governed by phase changes experienced by electro-rheological fluids.

According to the above-mentioned progress, it is clear that there is an important need for the design of novel display systems. The present research work focuses on the

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construction of a novel type of display system, which can be used to convert the sense of touch into images readily recognizable by the surgeon. Using the proposed system, surgeons can detect the softness of internal body organs by simply grasping that organ with a smart endoscopic grasper.

In the present study, a short description of a new softness sensor is presented. Arrays of four sensors are micro-fabricated and then incorporated into MIS grasper jaws. This presentation is followed by a description of the data acquisition system and the softness display algorithm, which is capable of constructing the tactile images. In Section II, the results obtained from the experiment are discussed. At the end, the conclusion and a description of future improvements are given.

II. Methods

A. System Design

The proposed system used for this study consists of an endoscopic grasper integrated with an array of tactile sensors, data acquisition interface (DAQ), and necessary signal processing algorithms (see Fig. 1).

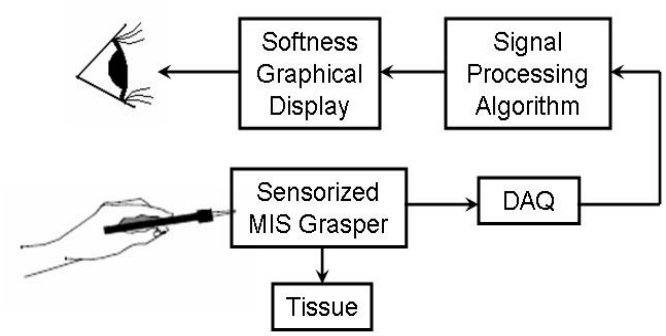


Fig. 1 The schematic diagram of the complete system

When the surgeon uses the endoscopic grasper to grasp tissue, the sensor array measures the softness of the tissue under each sensing element. The electrical outputs of piezoelectric sensing elements are then conditioned and transmitted to the data acquisition system. Using the data acquisition card (NI PCI-6225), the signals are amplified, filtered, digitized and processed by a computer. A computer code has been developed in LabView (version 7.1) environment for signal conditioning such as filtering out the line noise. A representation algorithm, as later elaborated in this paper, is used to map the extracted signal's features to a gray scale image. Using the constructed images, surgeon realizes the softness of the grasped object.

B. System Design

The sensor structure consists of an array of four individual sensors incorporated into the jaws of an endoscopic grasper. Each sensing element consists of four different parts(Fig 2.a and 2.b) namely, rigid cylinder(1), compliant cylinder (2), a sensing element, (3) and a silicon substrate (4). The rigid cylinder is machined from Plexiglas, 3 mm in diameter and 1 mm thick.

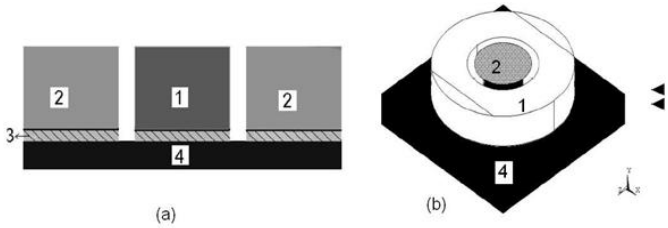


Fig. 2 The schematic diagram the tactile sensor showing a) the cross sectional and b) the three

The compliant ring shaped cylinder is micro-molded from liquid silicone rubber. For demonstration purposes, the outer diameter of the compliant cylinder is 6 mm and the inner diameter is 4 mm. The thickness of the cylinders is 1 mm. Due to fabrication limitations, there is a gap of 0.5 mm between the rigid and the compliant cylinders. This gap can be reduced to a negligible amount with a more precise fabrication process. A 25 μm bi-axially oriented, metalized and poled PVDF film is sandwiched between the cylinders and the substrate.

It has piezoelectric strain coefficients d_{31}, d_{32} and d_{33} of 20, 2 and −20 pC/N, respectively, and is used as the sensing element [21]. The PVDF film contains patterned aluminum electrodes right underneath the rigid and the soft cylinders.

The patterned PVDF films are glued by a nonconductive adhesive to a 0.5 mm thick silicon substrate. The output charges from both the PVDF films are fed to a data acquisition system through electrical connections. One of the important advantages of this design is the thermal insulation provided to the PVDF films by the rigid and the compliant cylinders. Due to this, when the grasper is in contact with different objects at different temperatures there are no spurious outputs due to pyroelectric effect of the PVDF film as the film is effectively isolated. During the actual testing, the object is assumed to have viscoelastic behavior similar to a real tissue.

C. Sensor Analysis

Fig. 3 shows the proposed analytical model of sensor-object configuration [22]. In this model, A_a is the area of the rigid cylinder, A_b is the area of the compliant cylinder, T_1 and $E_1$are the thickness and Young's modulus respectively of the modeled object under investigation, T_2 and E_2 are the thickness and Young's modulus respectively of the compliant cylinder,and c is the damping coefficient of the modeled object.

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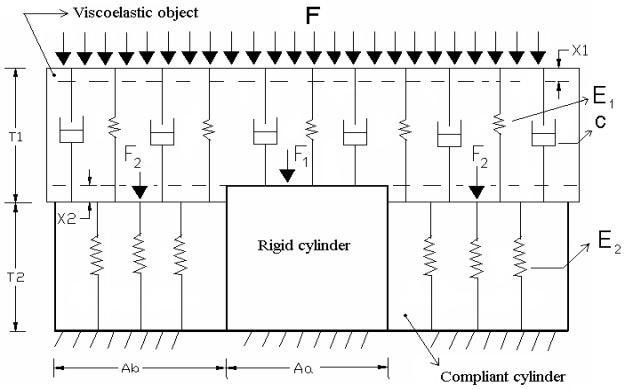


Fig. 3 Analytical model of sensor-object configuration

In this figure, the viscoelastic object is pressed to the sensor with a known force (F). A part of the applied force flows through the rigid cylinder and the rest flows through the compliant cylinder of the sensor. In this way, the parts of the object in contact with each element of the sensor are deformed to different extents. It is assumed that the viscoelastic object cannot take any bending load. Therefore, the rigid cylinder experiences only the applied load on the viscoelastic object just above it. The same assumption is true for the compliant cylinder.

The force ratio can be calculated from eq. [1-a] [22] .

$$\frac{F1}{F2}=\left[1+\frac{E_1T_2}{E_2T_1}\right]\left[\frac{1}{1-\exp(-\alpha t)}\right] \quad (1\text{-a})$$

where E is the modulus of elasticity, and α is $(E_1/T_1+E_2/T_2)/c$ and c is damping coefficient.

From Equation 1.a, when we put c = 0, $\alpha \rightarrow \infty$, the equation reduces to:

$$\frac{F1}{F2}=\left[1+\frac{E_1T_2}{E_2T_1}\right] \quad (1\text{-a})$$

D. Signal Processing

The processing software, developed in LabView 7.1 environment was specifically designed for graphical demonstration of softness of the grasped tissue. When tactile sensors touch an object, the output voltages of PVDF films underneath the rigid and compliant cylinders in each sensor are sensed and sent to data acquisition card. After these signals are filtered and conditioned, the ratio of the output voltages of rigid and compliant cylinders are calculated. The voltage ratio is equal to the ratio of forces applied to the compliant and hard cylinders. Once the voltage ratio is calculated, the modul of elasticity of the touched object can be found from the relationship 1.b. Then the softness which is proportional to the inverse of the modul of elasticity is calculated. The softness is then scaled and converted into grayscale value and displayed on the monitor.

Fig. 4.a show the jaws of an endoscopic grasper equipped with softness sensors. Two arrays of sensors are incorporated into the jaws of the grasper (Fig. 4.b).

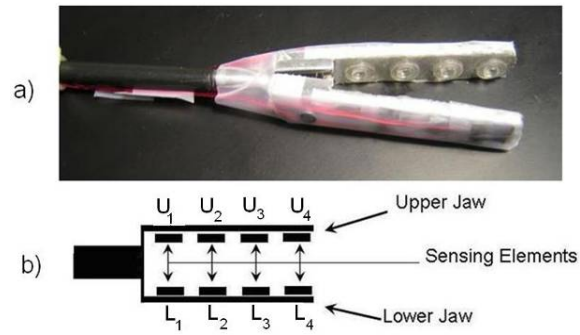


Fig. 4 a) Photograph of the grasper. b) The two arrays of sensing elements.

The complete softness image for the two tactile arrays consists of eight cells, arranged in two rows and four columns. Each cell in this 2x4 image is proportional to a sensing element in the two arrays of sensors.

The gray scale value of each cell can be obtained using following relationship:

$$[I]=([\sigma]/\alpha)K \quad (2)$$

in which matrices [I] and $[\sigma]$ represent the intensity and softness, respectively[23]. For this study, [I] and $[\sigma]$ take the following forms:

$$[I]=\begin{bmatrix} I_{U1} & I_{U2} & I_{U3} & I_{U4} \\ I_{L1} & I_{L2} & I_{L3} & I_{L4} \end{bmatrix}$$

$$[\sigma]=\begin{bmatrix} \sigma_{U1} & \sigma_{U2} & \sigma_{U3} & \sigma_{U4} \\ \sigma_{L1} & \sigma_{L2} & \sigma_{L3} & \sigma_{L4} \end{bmatrix}$$

Where σ_{ij} is the softness value sensed by each tactile sensor, $[I_{ij}]$ is the equivalent gray scale value for the softness. K is a coefficient which determines number of gray scale levels on the display. We considered 256 grayscale levels for displaying the tactile image, i.e. K=256. The symbol α is a coefficient which enables us to show different ranges of softness on the display. Fig. 5-a shows the resulting 2x4 image when the grasper is in touch with an object. The two right hand sensors of the grasper (U_4 and L_4) are engaged as indicated in Fig. 5.b.

To create a smooth transition between the columns and rows of the image, an interpolation between the gray scale values of the adjacent columns and rows is necessary. In step 7, a linear interpolation is performed to increase the number of columns from 4 to M. The resulted "2 x M" matrix, $[G]$ is shown in (3):

$$[G]=\underbrace{\begin{bmatrix} G_{U1} & G_{U2} & G_{U3}\cdots G_{UM} \\ G_{L1} & G_{L2} & G_{L3}\cdots G_{LM} \end{bmatrix}}_{M\ Columns}\Big\}2\ Rows \quad (3)$$

where:

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$$
\begin{aligned}
&G_{U1} = I_{U1},\\
&G_{U\,\frac{M+2}{3}} = I_{U2},\\
&G_{U\,\frac{2M+1}{3}} = I_{U3},\\
&G_{UM} = I_{U4},
\end{aligned}
\qquad (4)
$$

and,

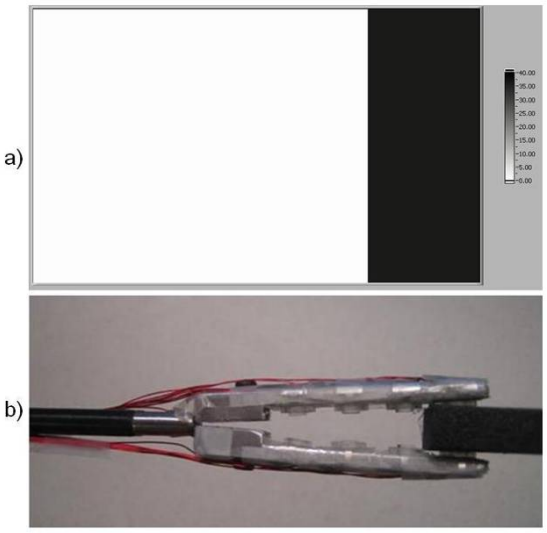


Fig. 5 Grasper is touching an elastomeric object a) Softness display representation. b) Photograph of the grasper and the grasped object

$$
\begin{cases}
G_{Uj} = I_{U1} + (j-1).\dfrac{I_{U2} - I_{U1}}{\frac{M-1}{3}} & ,\ 1 < j < \dfrac{M+2}{3}\\
G_{Uj} = I_{U2} + (j - \dfrac{M+2}{3}).\dfrac{I_{U3} - I_{U2}}{\frac{M-1}{3}} & ,\ \dfrac{M+2}{3} < j < \dfrac{2M+1}{3}\\
G_{Uj} = I_{U3} + (j - \dfrac{2M+1}{3}).\dfrac{I_{U4} - I_{U3}}{\frac{M-1}{3}} & ,\ \dfrac{2M+1}{3} < j < M
\end{cases}
\qquad (5)
$$

G_{Lj} can be obtained on a similar way.

In the next step, another linear interpolation, as indicated in (6) and (7), is implemented to increase the number of rows from 2 to *N*. The resulted matrix *H* can be shown as:

$$
[H] = \underbrace{\begin{bmatrix}
H_{11}\cdots & H_{1k} & \cdots H_{1M}\\
H_{21}\cdots & H_{2k} & \cdots H_{2M}\\
H_{31}\cdots & & \cdots H_{2M}\\
\vdots & H_{ik} & \vdots\\
H_{(N-1)1}\cdots & & \cdots H_{(N-1)M}\\
H_{N1}\cdots & H_{Nk} & \cdots H_{NM}
\end{bmatrix}}_{M\ Columns} \Big\}\, N\ Rows \qquad (6)
$$

where:

$$
H_{ik} = G_{Uk} + (i-1).\frac{G_{Lk} - G_{Uk}}{N-1}\ ,\ i = 1,\cdots,N \quad ,\ k = 1,\cdots,M \qquad (7)
$$

By following the above mentioned procedures, an image is constructed based on a matrix of 60x100 cells as shown in Fig. 6-a.

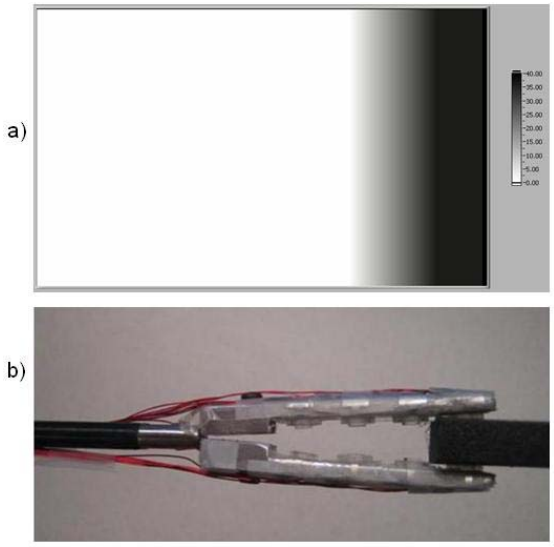


Fig. 6 a) The resulting tactile image after interpolation. b) Photograph of the grasper and the grasped object

III. Results and Discussions

The results of the experiments are shown as images in which the softness of grasped tissue is represented by grayscales. A scale in the right hand side of the graph , as shown in Fig. 6, shows the softness equivalent numerically. In this example, the two right hand sensors of the grasper (U_4 and L_4) are engaged both of them show the same softness value. It means that the grasped object has the same softness throughout its thickness. In Fig. 7, the upper and lower jaws are grasping two different materials with different softness.

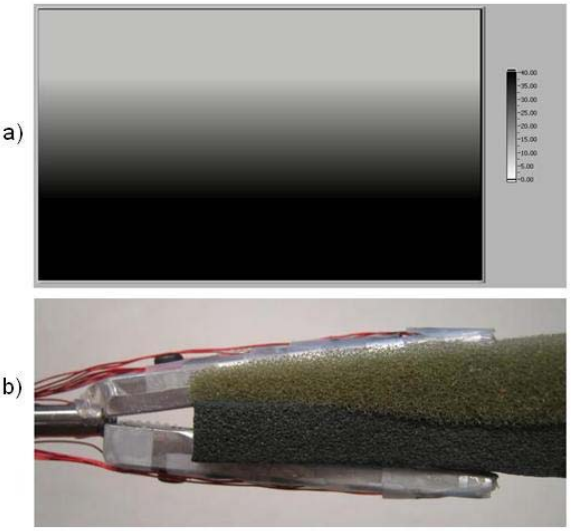


Fig. 7 Upper and lower jaws are touching two different objects. The objects are located in parallel. a) Tactile image display. b) Photograph of the grasper and elastomers

The material grasped by the upper jaw is softer than the other material. The resulting softness image shows two different grayscales on the upper and lower part of the display. Finally in Fig. 8, the two central sensors of the upper jaw, i.e. U_2 and U_3, are in touch with a soft material. Other sensors on the upper and lower jaws are in touch with a harder material.

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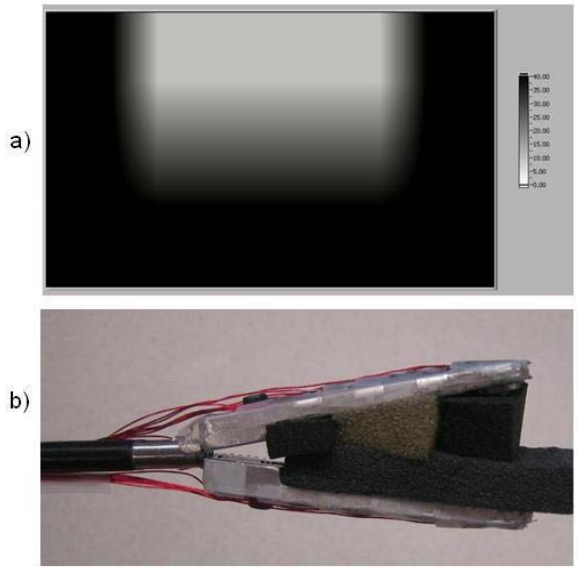


Fig. 8 Grasper is touching two different objects. One embedded object is located on top. a) Tactile image display. b) Photograph of the grasper and elastomers

IV. Summary and Conclusion

In this paper we have shown that it is possible to characterize various soft objects, including biological tissues, with a reasonable accuracy by using the proposed prototype endoscope grasper equipped with the array of softness sensors. The theoretical analysis of each sensor for both elastic and viscoelastic contact materials is made. The proposed graphical feedback system is also described.

This feedback system transmits the tactile signals from the grasper to a computer via the developed the signal processing and display system. The demonstrated visual data is the local softness of grasped tissue. Finally the grasper with its feedback interface and the graphical representation systems was tested and the results were discussed.

Work is currently underway in our lab to use the designed system for three dimensional localization of embedded lumps within tissue.

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