TACTILE SENSOR DESIGN FOR LUMP DETECTION IN BREAST TISSUE

*[1]Mustafa Zahid Yıldız,[2]Hamid Asadi Dereshgi, [1]Ali Furkan Kamanlı

[1] Faculty of Engineering, Department of Electric and Electronics Engineering Sakarya University, Turkey
[2] Faculty of Engineering, Department of Mechatronics Engineering Sakarya University, Turkey

mustafayildiz@sakarya.edu.tr

Abstract:The purpose of this study is the development of a novel system for detection of breast tumors in non-invasive way that can be used by doctors or patients. Our study consist of two parts. The first part is a specialized sensor containing an inductive sensor inside of a tissue-like silicon rubber robotic fingertip and a square shaped multi-metal-array to increase sensitivity. The whole system designed as a probe which has compact design and mobility. The system provides 16-bit resonance impedance and 24-bit inductance values, enabling sub-micron resolution for position-sensing in application. The tissue-like silicon properties were simulated and the linearity of the probe design against the pressure was analyzed. Tissue-like silicon rubber has hyper-elastic specifications. Force-displacement analysis showed %100 linear behavior. Tissue-like rubber silicon has also elastomer properties. The stress-strain analysis was made for 8 different point that showed non-linear behavior. With the current probe design, our detecting system is easy to use for every patients and health clinicians due to its mobility and easy access for different clinical environment. For the second part, to measure our system performance's sensitivity and specificity, comparison simulations will be performed.
In the simulation experiments, tumor-like inclusions embedded in tissue-like cylindrical silicon samples to make Phantom tissue in Virtual environments (VEs) will be designed. In VEs, the tumor-like tissue samples will be used in a various combination of stiffness and depth in phantom tissues. In real phantom experiments, the simulated phantoms will be created by the same silicon-rubber in similar conditions. The system will be embedded with the camera for tracking the every movement of robotic fingertip. The camera will record every location information (x,y) and combine it with the relative stiffness value which is taken from the sensor. And the topographical information of the tissue-like phantoms turned in to 2-D image. Breast examination can be done by human hands which have unique mechanism to sense vibrations called Pacinian corpuscle (response 60-700 Hz) and these sensory systems can be measured around the 200 Hz. In clinics, even though the clinical procedures are performed by the experts, it's difficult to detect small tumors and quantify the shape, location and stiffness. Because of these difficulties, tactile imaging sensors need to be used for diagnosis. As a future study, human palpation performance will be compared by our novel tactile sensor design embedded on a robotic fingertip.

Key words: Medical imaging, tactile sensor, lump detection, breast tumor.

Introduction

In recent years Breast cancer is the leading cause of death in western women aged 35-54. It is expected to reach 1 in 7 women by the year 2000 (American Cancer Society, 1997). Survival rates are highest when it is detected early and still confined to the breast. According to the statistics reported in 2008, breast cancer diagnosis has been made with an estimated 1.38 million new cases (23 percent of all the cancers) and the second most common cancer worldwide in both sexes (J.Ferley, 2010). About 1,685,210 new cancer cases are expected to be diagnosed in 2016 and invasive breast cancer will be diagnosed in about 246,660 women and 2,600 men. An additional 61,000 new cases of in situ breast cancer will be diagnosed in women. Breast cancer is the most frequently diagnosed cancer in women (American Cancer Society, 1997). It is crucial to detect Breast cancer in early stages. There are many ways to detect Breast cancer. Breast self-examination (BSE), clinical breast examination (CBE), Mammography, Ultrasound and MRI have important role for detecting breast cancer.

---

*Corresponding author: Address: Faculty of Engineering, Department of Electric and Electronics Sakarya University, 54187, Sakarya TURKEY.

Mammography is a low-dose x-ray procedure used to detect breast cancer at an early stage. Numerous studies have shown that early detection with mammography helps save lives and increases treatment options. However, like any screening tool, mammography is not perfect. For example, it can miss cancers, particularly those in women with very dense breasts, and also detects cancers that would never have caused harm, resulting in some over-diagnosis. And also differences in breast tissue, inefficient sensitivity, and small tumor size can cause false-diagnosis which can cause over-diagnosis. Some of the unwanted results of over diagnosis are increasing number of biopsies, higher-rate of invasive procedures, psychological effects of a patient and higher cost. Mammography is not recommended who is under 30 and have breastfed previous year. Because of the age breast tissue is dense and is hard to detect any cancerous tissue with mammography.

Magnetic resonance imaging (MRI) is a noninvasive method that reveals anatomical details in vivo and detects lesions for diagnosis. Although standard breast MRI cannot clearly delineate breast cancer, contrast-enhanced MRI enables the detection of breast masses with high sensitivity. MRI uses a powerful magnetic field and radio waves to produce images of the body. MRI is good at imaging dense breasts of younger women, breasts containing implants, which are often a problem for mammography owing to possible leak in the implant or rupture due to the squeezing, and smaller lesions often missed by mammography. MRI also helps to determine the stage of breast cancer. However, MRI requires the patient to lie down for half an hour to an hour and half without moving, which can be uncomfortable (Kuhl.JK, 1997). The identification of breast cancer using MRI is largely dependent on the enhancement of malignant lesions after IV administration of contrast agent, resulting in visible areas with both morphologic and kinetic features. However, enhancement on MRI is not limited to malignancies or discrete benign lesions of the breast (Müller-Schimpfle M ,1997, Reichenbach JR ,1999, Delille JP,2005). One of the main disadvantages of the MRI is that limiting specificity is the incidence of benign enhancing lesions and benign background enhancement that may be misdiagnosis that leading to an increased false-positive biopsy rate (Imaginis, 2001). Also during the MRI process patients have to lie down without a movement about half an hour which gives them discomfort and with the smallest movement the procedure needs to be repeated.

Ultrasound is a method that uses high frequency sound waves to detect tumors in tissue. There are several types of Ultrasound modes: B-mode, Doppler mode etc. B-mode capture reflected sounds and create and matrix format for the image (C.M. Sehgal,2006, C.F. Nemec,2007). And it can be used in pregnant women whom cannot use Mammography. And the results are depends on the experience of the clinical expert and the situation of the patient. Also clinical procedures have a standardization and interference in procedures have different results. In Doppler mode veins and tissue used for detecting tumors. Frequency shift calculated with the Doppler Effect so that flow can be estimated and visualize the breast tissue(D.O. Cosgrove,1993 , S. Raza,1997).

Microwave imaging and Elastography are used for breast cancer detection. Elestography detect different roughness between the tissues. Microwave imaging detect the dielectric constant and conductivity difference between the tissues (G.A. Ybarra, 2007).

Breast Self Examination and Computed Breast Examination uses human palpation. Human sensory feedback has a really important role in human interactions (B. Güçlü,2005, Bolanowski SJ,1988). Unlike the vision of that Human eyes provide us the sensory system in our body (haptic) can sense and respond in their own unique way towards to every interactions (Gescheider GA,1988, 2002). Haptic systems needs to obtain more data from sensory systems. Haptic system inputs; force, movement needs to be converted as an input/output form for interactions. Developing a sensor with a tactile feedback has some challenges. Vibrations and sensing has its unique values in human touch (M.Z Yıldız,20013, B. Güçlü,2005, Bolanowski SJ,1988, Gescheider GA,1988 & 2002) and making a prosthetic finger human-like modeling is a challenging area which has obstacles like sensing a high frequency vibrations. Human hands have unique mechanism to sense vibrations called Pacinian corpuscle (response 60-700 Hz) and these sensory systems can be measured around the 200 Hz (V. B. Mountcastle 1972, G. Westling 1987, A. J. Brisben 1999). Because of these challenges artificial sensing system development researches has been made which is named Tactile İmaging (TI).

Tactile imaging is a non-invasive procedure that used for detecting cancerous tissue. TI used for mapping the interested area with sensors. TI is superior to BSE and CBE because every examiner can sense different shapes and geometries in different areas so the results are quantative and subjective. Sensors can detect difference between the cancerous tissue and healthy tissue with different sensor types (A. Samani, 2003, P.S. Wellman, 1999, A. Sarvazyan, 1994). With TI size, shape and depth of the cancerous tissue can be detected. Geometric properties and stiffness vary between the benign and malignant tissues as reported in (A.R. Skovorda, 1995) and (T.A. Krouskop, 1998). TI is a method that newly exploited. There is a limited number of device that commercially available (Medical Tactile Inc, 2012). Some study groups work on different sensor types. Accelerometers (R. D. Howe, 1989), piezoelectric polymers (P. Dario, 1994, J. S. Son, 1994, Y. Yamada, 1994 , P. Dario, 1994) magneto-inductance (J. Vranish, 1986), and ultrasonic technologies (B. Hutchings, 1994) , (S. Ando, 1995) sensor array with the photo detector (] M. Ayyıldız, 2013). These sensors used variety of applications however those sensors have some fragile sensing mechanism. With the (Medical Tactile Inc, 2012) product a study has been made about 110 patient (V. Egorov, 2008) and a study has been made with the silicon model along with the patients (C.S. Kaufman, 2006). Their experiments was performed in two consecutive steps: 1) a general examination by linear sliding of the probe, and then 2) a local examination by making circular motions. If any suspicious tissue have seen then the second step performed.

In current design we propose single point tactile detection robotic fingertip embedded with the high resolution camera. The designed probe's every movement is going to be tracked with the camera. The high resolution inductive sensors value combined with the location information which is obtained from the camera. With this method the topographical shape of the interested area is going to be mapped. And 2-D image of the interested area will be revealed without any quantative results. For the experiment part tumor-like properties is going to be placed in tissue-like silicon rubber phantoms. The tumor-like tissue samples used in a various combination of stiffness and depth in phantom tissues. Every sample will be examined according to their relative stiffness. Human hands unique sensing mechanism to sense small objet. An expert clinician can detect some of the lumps in the soft tissue but most of them pass through without any detection. And human palpation can change according to every person which means the results will be subjective if any of the procedure only done by the human hands because of these challenges we designed a system with high sensitivity and specificity. After the ethical committee permission to make non-invasive human studies. The performance will be compared by human hands.

Materials and Method

2.1. Design of our TI system

Our tissue-like silicon rubber robotic fingertip designed as a probe. Simulated all probe dimensions and materials are corresponding to the manufacturing technology and available materials on the market. The outer skeleton of probe is produced in 3D printer (thermoplastic polymer. In this part, we focused on design and analysis of a tactile probe molding and mechanical analysis by using Solid works program. SolidWorks is a solid modeler, and utilizes a parametric feature-based approach to create models and assemblies. The outer skeleton of probe we are fabricated in 3D printer (thermoplastic polymer). In this study we also needed a material that is similar to human skin on that part the device should come into contact with a cancerous tumor. But there are ethical and safety issues associated with obtaining alternative method human tissue. However after reviewing, we find dragon skin silicon on the market. Dragon skin silicones are used for a variety of applications ranging from creating skin effects and making production molds for casting a variety of materials. Due to the superior physical properties and flexibility, we decided to use this material in our project. It must be said that, it is used for medical prosthetics and cushioning applications. Particular focus was shown to find a robust tactile sensor that has the sensitivity and response to all tactile sensing modalities found in the human fingertip. Our TI system consist of %100 integrated sensor elements (TI LDC1000 EVM) arranged in a single point shape inductive sensor. The side length and the height of our TI sensor are 1.6 and 2.1 cm, respectively and sensor element is located in 1.4 cm of the silicon layer. Typical characteristic of the sensor shown in Figure 1 and Figure 2 shown the axial sensing of a sensor. Our sensor measures the parallel impedance of an LC resonator and has an Inductance-to-Digital Converter for the task. It accomplishes this task by regulating the oscillation amplitude in a closed-loop configuration to a constant level, while monitoring the energy dissipated by the resonator. The sensor element are powered by an external, regulated power supply (5V DC). Metal pieces was located above and bottom of the sensor and silicon tween them as shown in Figure 3 and characteristics of tactile probe are in table 1. Inductive proximity sensors are used for non-contact detection of metallic objects. The system provides 16-bit resonance impedance and 24-bit inductance values, enabling sub-micron resolution for position-sensing to locate metal array inside of the silicon. After 10 mm of silicon the sensor is not capable of sensing the outside metals.

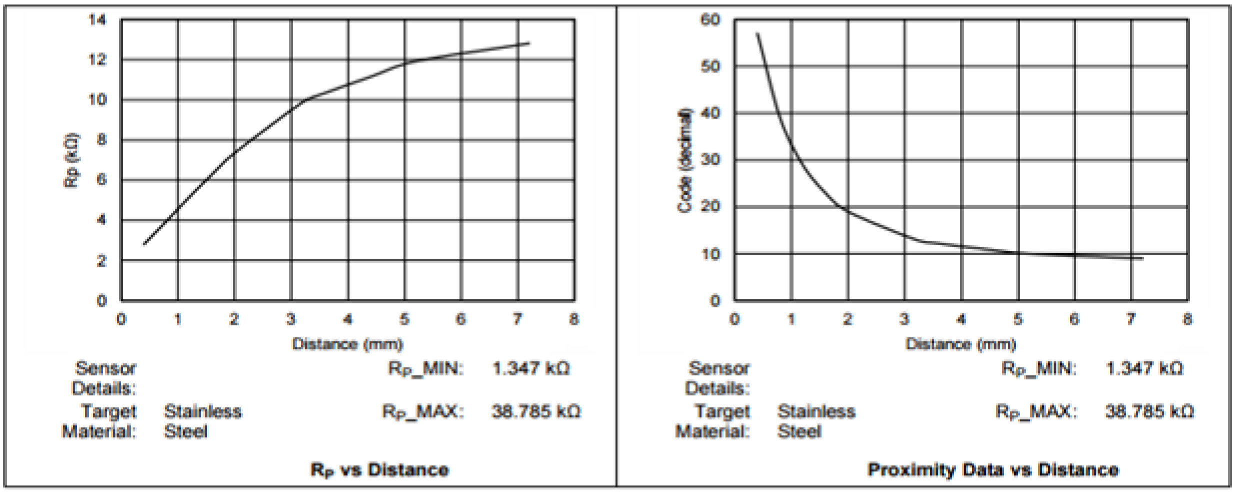


Figure 1. Typical characteristic of an inductive sensor.

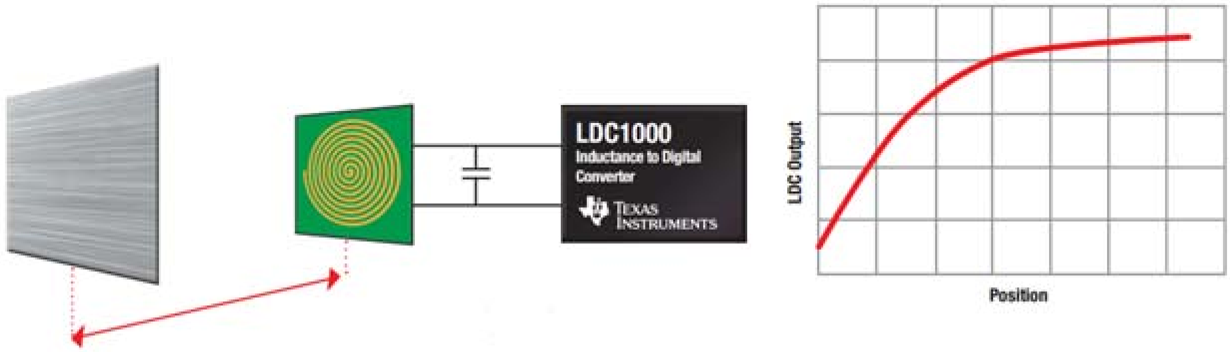


Figure 2. Axial sensing of a Sensor.

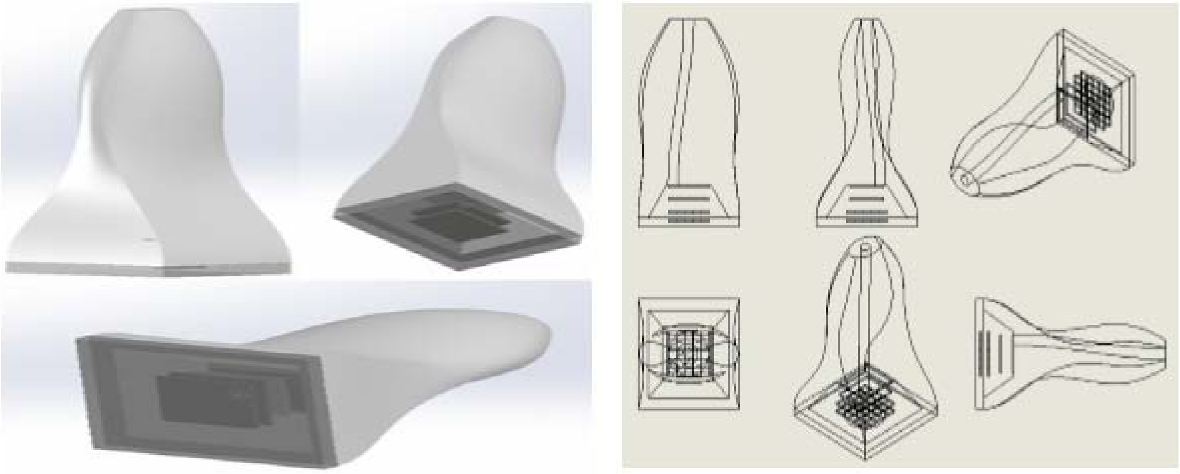


Figure 3. Geometric view of tactile probe/Metal array shape inside of a tissue-like silicon.

Table 1. Characteristics of tactile probe.

Thickness of silicon	19 mm

Dimension of large metal piece	16mm × 21mm × 1mm
Dimension of each small metal pieces	5mm × 5mm × 1mm
Dimension of sensor	16mm × 21mm × 1mm
Dimension of probe touch section	50 mm × 50 mm
Length of probe	94 mm
Total number of small metal pieces	50
Exoskeleton material	Thermoplastic polymer
Silicon material	Rubber

In this system Data acquisition hardware acts as the interface between the computer and the outside world. It primarily functions as a device that digitizes incoming analog signals so that the computer can interpret them. Other data acquisition functionality includes the following:

- Analog input/output
- Digital input/output
- Counter/timers
- Multifunction - a combination of analog, digital, and counter operations on a single device

In this case our changeable value is Eddie current which happen to change when the metal array moved inside of the tissue-like silicon shown in Figure 4-5.

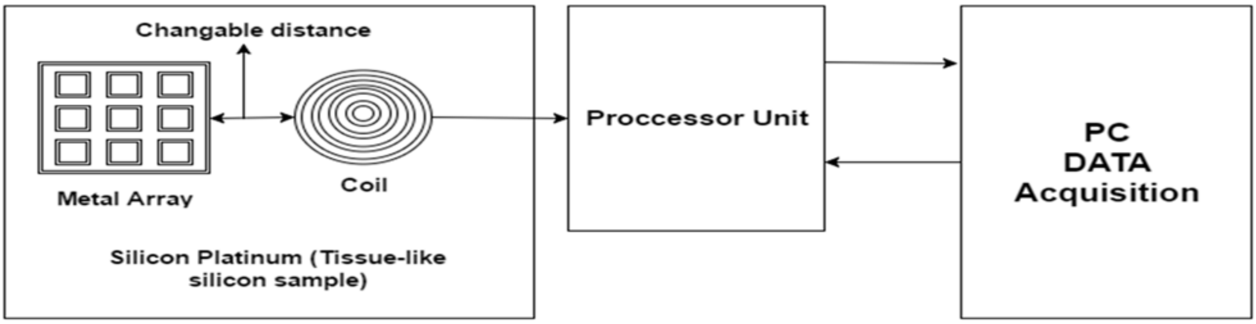


Figure 4a. Data acquisition units of the proposed TI system.

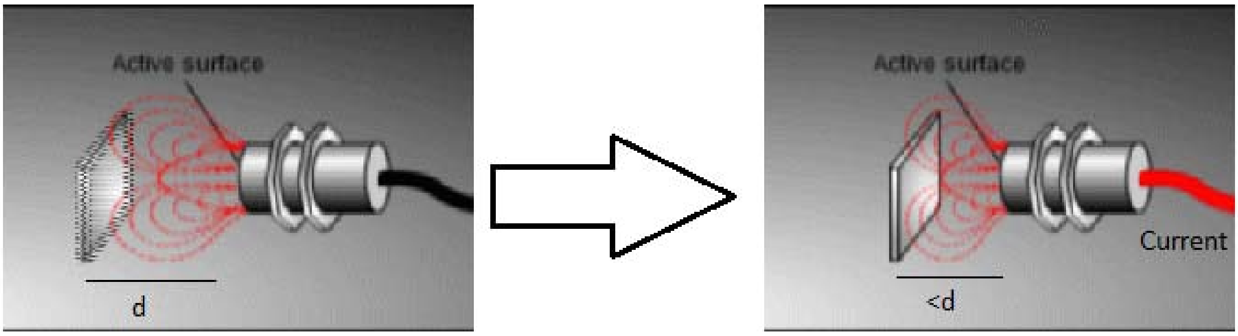


Figure 4b. Eddie current change due to metal array movement.

Results

In this section, the simulation results of the proposed sensor are shown. The silicon rubber that used in this study has the hyper-elastic material behavior and by the finite element method, stress and strain relations and displacement-force graphs were plotted. By giving the correct Poisson ratio from the datasheet of the materials to the software (Solid Works), the material showed isotropic linear property. Because the forces were quite low, the silicon rubber stay in the elastic region of the material. Therefore, a multilinear elastoplastic model was not chosen for the static analysis.

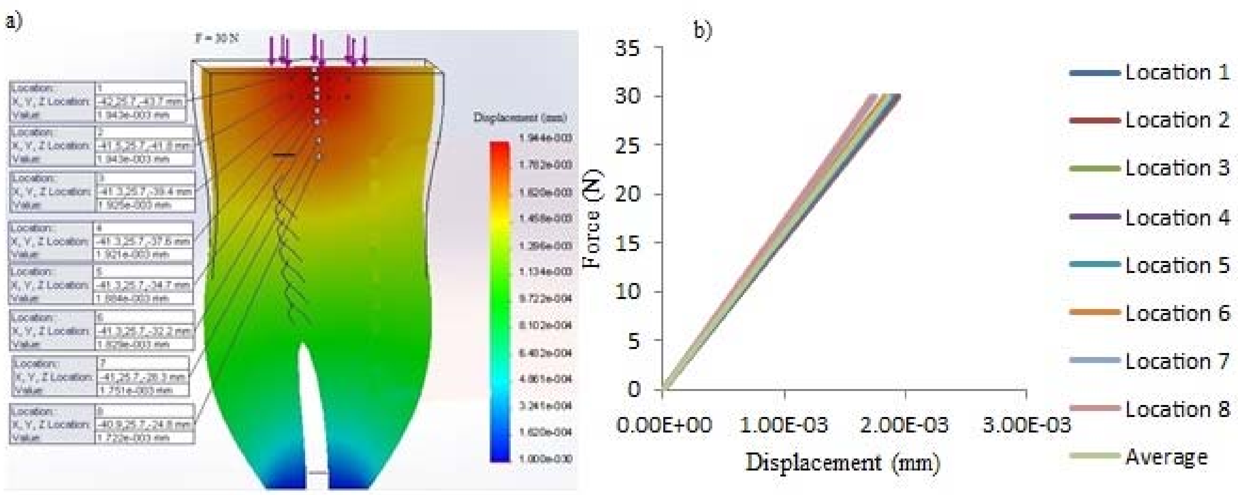


Figure 5. a) Static force (F =30 N) is applied to the silicon. b) Displacement graph of Dragon Skin silicon in the results of applied forces

Elastomers have the non-linear elastic stress-strain behavior and the term “elastomer” is basically used for materials which shows silicon-rubber properties. The reason for this behavior can be explained that, as it is shown on the stress-strain curve, the maximum force applied to the sensor is 30 N. This force is considered quite low level. Upon unloading this small force, there will be any permanent deformation on the material. In practice, this material behavior is considered as incompressible. On the Figure 6, the simulation results shows the stress-strain behavior of our sensor upon the applied forces between 0.1-30 N.

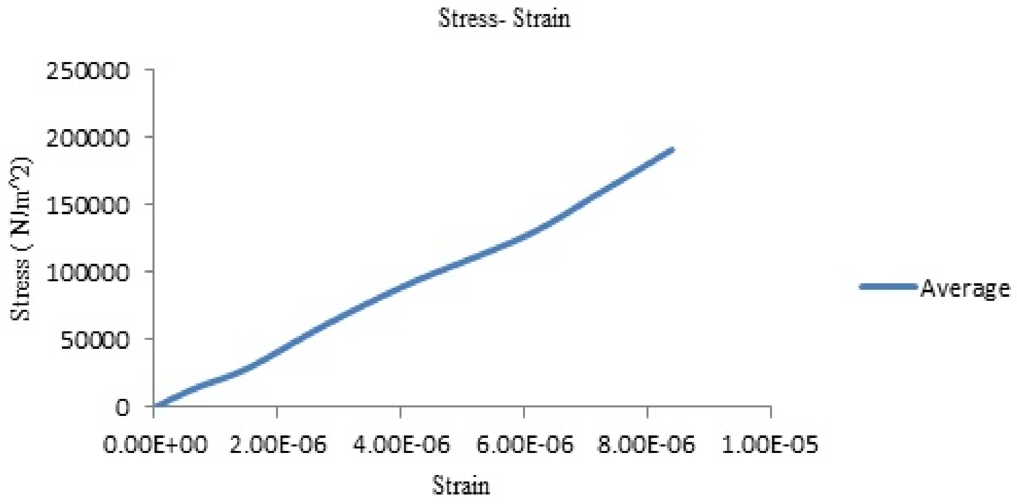


Figure 6. Dragon Skin silicon material behavior.

Elastomers (like Dragon Skin is platinum silicon) typically have considerable strains at small loads (means a very low modulus of elasticity, for example just 30 N). The material is nearly incompressible, so the Poisson's ratio is very close to 0.5. Their loading and unloading stress-strain curve is not the same, depending on different influence factors (time, static or dynamic loading, frequency etc.). In Figure 7, all the stress-strain relation curves were shown for the different depths at the center of the sensor.

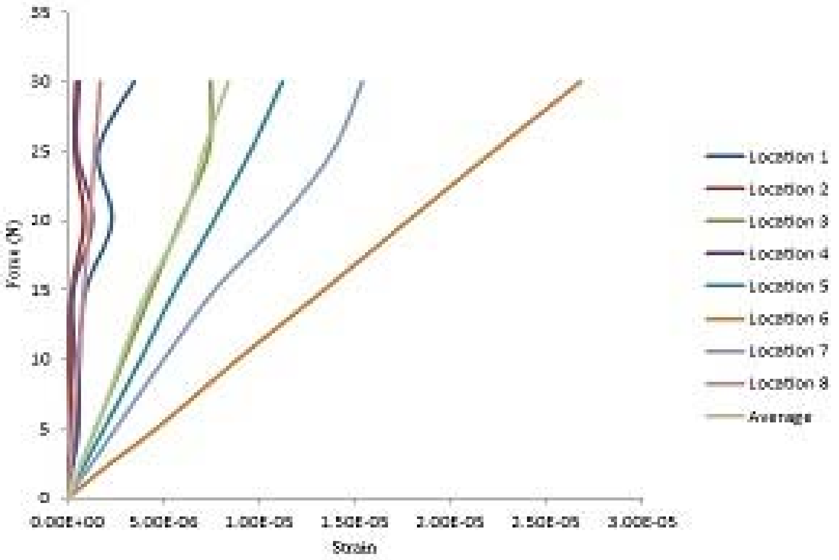
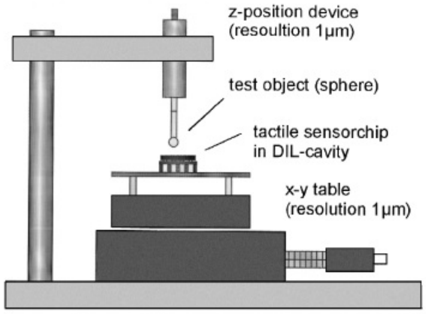


Figure 7: The results of strain in different applied forces to Dragon Skin (platinum silicone) material.

Discussion

We carried out our probe simulation in the SolidWorks, because the SolidWorks simulation uses the displacement formulation of the finite element method to calculate component displacements, strains, and stresses under external loads. In the SolidWorks analysis results non-linear hyperelastic materials behavior was observed. The analysis of rubber parts should be carried out using nonlinear stress analysis methods, due to their complex load deformation relationship. Due to the use of low loads, we thought in this area elastic behavior of materials would be remained on the upshot we use SolidWorks module for isotropic materials. In the next stage we are focused on design and analysis of multi module hyperelastic material models. In table 2, we will discuss how the different groups are studied and how we can do it.

Ref.	Method	Figure	Explanation
M. Leineweber et al, 200.	New tactile sensor chip with silicone rubber cover		Actually, the tactile sensor was used in that paper is based on the FhG-IMS pressure sensor and it has advantage and disadvantage. Sensor output is equal to mechanical analysis but the sensor needs to be calibrated for all different geometry.

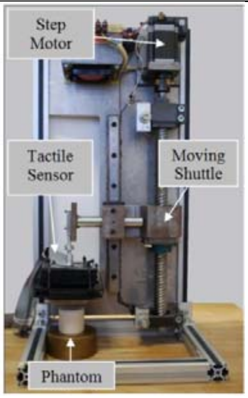
M. Ayyıldız et al, 2013.	Tactile sensor array with photodiode and tissue like phantom		Sensor array used with led potodetector and with this way the tissue like phantom can be mapped.

Table 2. Different study group that has made tactile sensor for lump detection.

Our current design have some advantages comparison to the other study groups that shown in Table 2. Tissue-like silicon rubber as shown in Figure.8 is 100% linear which means that after the acceptable force (0-30N similar to the human finger) the material will turn in to previous state of the matter. So it can be called as a finger-like probe that can be used numerous times. İnductive sensing is capable of sensing sub-micron changes in distance. And accurate sensing is possible with inductive sensing. With our design we can detect even the smallest particle because our sensor and metal array placed 0-0.5 cm distance to each other as shown in Figure.9. And isolated from the outside interference with our silicon properties which means even the smallest lump detection in soft tissues will be possible.

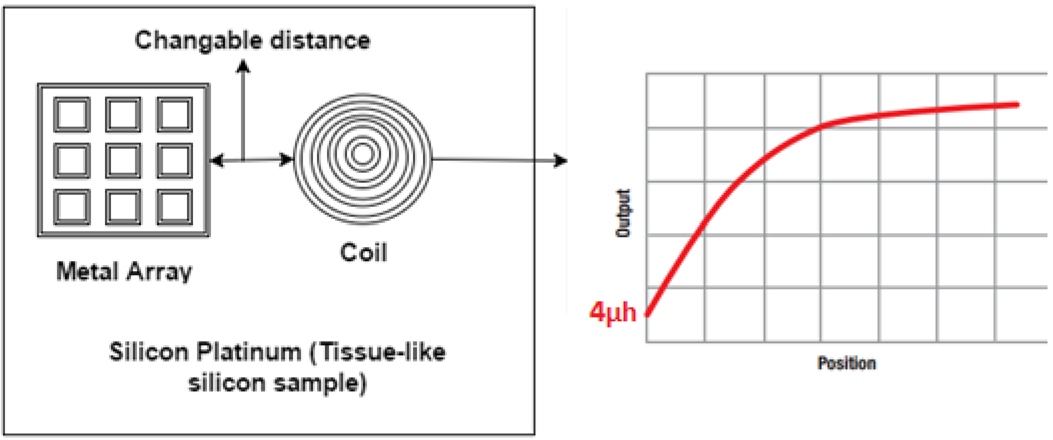


Figure 8. Because of our probe design The starting point of the sensor is 4μh and the our measurement points inside of the linear area of the sensor.

Conclusions

In this study, our choice to carry out the probe simulation was the SolidWorks, because the SolidWorks simulation uses the displacement formulation of the finite element method to calculate component displacements, strains, and stresses under external loads. In the SolidWorks analysis results non-linear hyperplastic materials behavior was observed. The analysis of rubber parts should be carried out using nonlinear stress analysis methods, due to their complex load deformation relationship. Due to the use of low loads, we thought in this area elastic behavior of materials would be remained on the upshot we use SolidWorks module for isotropic materials. In the next stage we are focused on design and analysis of multi module hyperelastic material models. These are directions in which we plane to continue our work.

Acknowledgements

This study was supported by Sakarya University Research Fund (BAP) no.2014-01-00-001 to Assist. Prof. Dr. Mustafa Zahid Yıldız. The authors thank to Professors from Mechatronics Engineering Department of Technology Faculty for their motivations and suggestions in the initial design of the experiments, and for critical comments on the paper. The authors are grateful to Biomedical Instrumentation Lab. Students for their contributions.

References

A.R. Skovorda, A.N. Klishko, D.A. Gusakian, E.I. Maevskii, V.D. Ermilova, G.A. Oranskaia, and A.P. Sarvazian, (1995)*"Quantitative Analysis of Mechanical Characteristics of Pathologically Altered Soft Biological Tissues,"* Biofizika, (vol. 40, no. 6, pp. 1335-1340).

A. J. Brisben, S. S. Hsiao, and K. O. Johnson, (1999 *)"Detection of Vibration Transmitted Through an Object Grasped in the Hand,"* Journal of Neurophysiology, (vol. 81, pp. 1548–1558).

A. Samani, J. Bishop, C. Luginbuhl, and D.B. Plewes,(2003) *"Measuring the Elastic Modulus of Ex Vivo Small Tissue Samples,"* Physics in Medicine and Biology,(vol. 48, no. 14, pp. 2183-2198).

A. Sarvazyan, D. Goukassian, E. Maevsky, G. Oranskaja, G. Mironova, V. Sholokhov, and V. Ermilova, (1994) *"Elasticity Imaging as a New Modality of Medical Imaging for Cancer Detection,"* Proc. Int'l Workshop Interaction of Ultrasound with Biological Media, pp. 69-81.

American Cancer Society (1997) Surveillance Research, http://www.cancer.org/statistics.

B. Hutchings and A. Grahn, (1994) *"Multiple-Layer Cross-Field Ultrasonic Tactile Sensor,"* in *IEEE International Conference on Robotics and Automation*, (pp. 2522–2528).

B. Güçlü, S.J. Bolonowski (2005) "Vibrotactile thresholds of the Non-Pacinian I channel: II. Predicting the effects of contactor location on the phalanx" Somatosensory & Motor Research ,(Volume 22, Issue 1-2, , 57-68).

Bolanowski SJ, Gescheider GA, Verrillo RT, Checkosky CM (1988*) "Four channels mediate the mechanical aspects of touch"*. J. Acoust. Soc. Am. (84: 1680–1694).

C.M. Sehgal, S.P. Weinstein, P.H. Arger, and E.F. Conant, (2006) *"A Review of Breast Ultrasound,"* J. Mammary Gland Biology and Neoplasia,(vol. 11, no. 2, pp. 113-123).

C.F. Nemec, J. Listinsky, and A. Rim,(2007) *"How Should We Screen for Breast Cancer? Mammography, Ultrasonography, MRI,"* Cleveland Clinic J. Medicine, (vol. 74, no. 12, pp. 897-904).

C.S. Kaufman, L. Jacobson, B.A. Bachman, and L.B. Kaufman, (2006 *)"Digital Documentation of the Physical Examination: Moving the Clinical Breast Exam to the Electronic Medical Record,"* Am.J. Surgery, (vol. 192, no. 4, pp. 444-449).

Delille JP, Slanetz PJ, Yeh ED, Kopans DB, Halpern EF, Garrido L. (2005*) Hormone replacement therapy in postmenopausal women: breast tissue perfusion determined with MR imaging—initial observations.* Radiology 2005; 235:36–41

D.O. Cosgrove, R.P. Kedar, J.C. Bamber, B. al-Murrani, J.B. Davey, C. Fisher, J.A. McKinna, W.E. Svensson, E. Tohno, and E. Vagios, (1993) "Breast Diseases: Color Doppler US in Differential Diagnosis," Radiology, vol. 189, no. 1, pp. 99-104.

G.A. Ybarra, W.T. Joine, Q.H. Li, and J.P. Stang, (2007) *"Emerging Technology in Breast Imaging and Mammography,"* Microwave Breast Imaging, J. Suri, et al., eds., pp. 1-12, Am. Scientific.

G. Westling and R. S. Johansson, (1987) *"Responses in Glabrous Skin Mechanoreceptors During Precision Grip in Humans,"* Experimental Brain Research, (vol. 66, pp. 128–140).

Gescheider GA (1988)*"Psychophysical Scaling"* Annual Review of Psychology Vol. 39: 169-200.

Gescheider GA (2002) *"A four-channel analysis of the tactile sensitivity of the fingertip: frequency selectivity, spatial summation, and temporal summation"* Somatosensory & Motor Research (Volume 19, Issue 2, 2002, 114-124)

Gescheider GA, B. Güçlü, (December 2005)*"Spatial summation in the tactile sensory system: Probability summation and neural integration"* Somatosensory and Motor Research; (22(4): 255–268).

Imaginis, (2001) "*Scientists Find Mammography is Still 'Gold Standard' for Breast Cancer Detection but Recommend Research into More Accurate Methods,"* http://www.imaginis.com/breast-healthnews/ scientists-find-mammography-is-still-quot-gold-standardquot- for-breast-cancer-detection-but-recomme,.

J.Ferlay, H.R. Shin, F. Bray, D. Forman, C. Mathers, and D.M. Parkin, (2010) *"Estimates of Worldwide Burden of Cancer in 2008: GLOBOCAN 2008,*" Int'l J. Cancer, vol. 127, pp. 2893-2917.

J. S. Son, E. A. Monteverde, and R. D. Howe, (1994) "A Tactile Sensor for Localizing Transient Events in Manipulation," in *IEEE International Conference on Robotics and Automation*,(pp. 471–476).

J. Vranish, “Magnetoinductive skin for robots, (1986)” *in IEEE International Conference on Robotics and Automation,”* , (vol. 3, pp. 1292–1318).

Kuhl CK, Bieling HB, Gieseke J, et al. Healthy (1997) *“Premenopausal breast parenchyma in dynamic contrast-enhanced MR imaging of the breast: normal contrast medium enhancement and cyclicalphase dependency.”* Radiology; 203:137–144

M. Ayyıldız, B. Güçlü, Mustafa Zahid Yıldız, Ç.Başdoğan (2013) *“An Optoelectromechanical Tactile Sensor for Detection of Breast Lumps”* IEEE TRANSACTIONS ON HAPTICS, (VOL. 6, NO. 2, ,145-155).

Mustafa Zahid Yıldız, B. Güçlü, (March 2013)*“Relationship between vibrotactile detection threshold in the Pacinian channel and complex mechanical modulus of the human glabrous skin”* Somatosensory and Motor Research,; (30(1): 37–47)

Michael Leineweber, Georg Pelz, Michael Schmidt, Holger Kappert, Gunter Zimmer, (2000) “New tactile sensor chip with silicone rubber cover”, Sensors and Actuators, (Vol. 84, 236–245).

Müller-Schimpfle M, Ohmenhauser K, Stoll P, Dietz K, Claussen CD. (1997) *Menstrual cycle and age: influence on parenchymal contrast medium enhancement in MR imaging of the breast.* Radiology; 203:145–149

Medical Tactile Inc. , 2012 “SureTouch,” http://www.medicaltactile.com.

P.S. Wellman, R.D. Howe, E. Dalton, and K.A. Kern, (1999*) “Breast Tissue Stiffness in Compression is Correlated to Histological Diagnosis,”* http://biorobotics.harvard.edu/pubs/1999/ mechprops.pdf.

P. Dario, D. de Rossi, C. Domenici, and R. Francesconi, (1984) *“Ferroelectric Polymer Tactile Sensors with Anthropomorphic Features,”* in *IEEE International Conference on Robotics and Automation*,(pp. 332–340).

P. Dario, M. Rucci, C. Guadagnini, and C. Laschi, (1994) *“An Investigation on a Robot System for Disassembly Automation,”* in *Proceedings of IEEE International Conference on Robotics and Automation*, (vol. 4, pp. 3515–3521).

Reichenbach JR, Przetak C, Klinger G, Kaiser WA. (1999) *Assessment of breast tissue changes on hormonal replacement therapy using MRI: a pilot study.* J Comput Assist Tomogr; 23:407–413.

R. D. Howe and M. R. Cutkosky, (1989) *“Sensing Skin Acceleration for Slip and Texture Perception,”* in *IEEE International Conference on Robotics and Automation*, (pp. 145–150).

S. Raza and J.K. Baum, (1997) *“Solid Breast Lesions: Evaluation with Power Doppler US,”* Radiology, (vol. 203, no. 1, pp. 164-168).

S. Ando and H. Shinoda, (1995) “*Ultrasonic Emission Tactile Sensing,” IEEE Control Systems*, (vol. 15, pp. 61–69).

T.A. Krouskop, T.M. Wheeler, F. Kallel, B.S. Garra, and T. Hall, (1998*) “Elastic Moduli of Breast and Prostate Tissues under Compression,”* Ultrasonic Imaging, (vol. 20, no. 4, pp. 260-274).

V. Egorov and A.P. Sarvazyan, (Sept. 2008) *“Mechanical Imaging of the Breast,”* IEEE Trans. Medical Imaging, (vol. 27, no. 9, pp. 1275-1287).

V. B. Mountcastle, R. H. LaMotte, and G. Carli, (1972 *) “Detection Thresholds for Stimuli in Humans and Monkeys: Comparison With Threshold Events in Mechanoreceptive Afferent Nerve Fibers Innervating the Monkey Hand,”* Journal of Neurophysiology, (vol. 35, pp. 122–136).

Y. Yamada and M. R. Cutkosky, (1994) *“Tactile Sensor with 3-Axis Force and Vibration Sensing Functions and Its Application to Detect Rotational Slip,” IEEE International Conference on Robotics and Automation*,(pp. 3550–3557).