Design and Construction of a New Capacitive Tactile Sensor for Measuring Normal Tactile Force

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ABSTRACT

This paper presents the design, construction and testing of a new capacitive tactile sensor for measurement of normal tactile force. The operation of proposed sensor has been investigated in ASTABLE and MONOSTABLE circuits. According to the results of these circuits the deviation of ASTABLE circuit results is less than MONOSTABLE circuit results. In addition, the results obtained from ASTABLE circuit are less separable compared to those of MONOSTABLE circuit. Remarkable advantages of this circuit are its simplicity and low energy consumption aside from its ability to be miniaturized which makes it a good substitute for the sensor in robotics and medical sciences such as minimally invasive surgery (MIS).

KEYWORDS

Tactile sensor, Capacitive Sensor, Tactile Force.

1. INTRODUCTION

Tactile sensing is a process which determines physical specifications and environmental events via contact with objects. A tactile sensor is a system which can measure some physical specifications via contact [1]. A tactile sensor can be used to specify needed force for grasping and holding certain object precisely [2]. Adequate force for grasping can be determined based on the weight that it can be used [3].

Sensors are necessary for development of intelligent systems, especially in the field of medicine. In the last decades sensors have been used in different stages in medical fields such as diagnosis, treatment and rehabilitation widely [4]. One of the important applications of sensors in treatment field is in the smart instruments used in Minimally Invasive Surgeries (MIS) [5]. Tactile sensing and vision are necessary for performing surgeries. Tactile sensing has the certain application of distinguishing different tissues and large vessels during surgery. These sensors are used to determine physical specifications of different tissues such as shape, location, size, roughness, softness, etc. Therefore, it is important to perform a perfect surgery as the surgeon's tactile sensing and vision are decreased in telesurgery [6]. In the cases that the interfaces between the surgeon and site of surgery are far from each other the surgeon's sensing would be decreased. So using equipment for transferring information from site of surgery is necessary for surgeon [7], [8].

Recognition and removal of a tumor from the body, for instance, are done in several stages which consist of distinguishing the tumor, assessment of its shape and size, recognition of main vessels and capillaries near the tumor, recognition of nerves and sensitive tissues near the tumor, removing the tumor with less trauma to its adjacent tissues and removing this part from the site of surgery with appropriate force.

Tactile sensors work according to the physical phenomena such as piezoelectric, piezoresistive, magnetic, and capacitive sensors. Piezoelectric sensors operate based on changes of the electrical voltage produced by the pressure changes, piezoresistive sensors act with the resistive changes, magnetic sensors act with the changes in flow of magnetic field, and capacitive sensors act with changes in capacity [9].

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Many tactile sensors have been designed and constructed for different applications in the last decades. A tactile sensor with MEMS structure has been presented for robotic application by Mei et al. (2000). This sensor has soft contact surface and it can measure 50N in perpendicular direction and 10N in X and Y directions [10]. A capacitive tactile sensor has been designed by Chappell and Elliott (2003) used in artificial hand. This sensor can estimate the force with strain measurement. The substance which is used between the capacitor plates has an elastic behavior. Acting force on the plates changes the capacitance measured via an oscillator circuit with frequency output [11].

A type of endoscopic tactile sensor has been constructed with semi conductive micro strain gages by Dargahi and Najarian (2004). This sensor measures amount and location of the inserted force which changes from 0.5N to 50N. This tactile sensor completes with endoscopic clamp [12]. A tactile sensor which is applicable in robotic, operates according to the contact and slip specifications. Contact is used for measuring contact force in a point and slip is used for measuring object movement with respect to the sensor [13], [14].

This paper presents design, construction, and testing of a new capacitive tactile sensor for measurement of normal tactile force. The main advantage of this sensor is that it can measure an appropriate range of applied force on the biological tissues. On the other hand, its biocompatible coating makes it more adequate when being in contact with these tissues.

A capacitive sensor array has more sensitivity, linear response and less hysteresis compared to the piezoelectric sensors [15]. Also, capacitive sensors can be used for determining changes of dielectric coefficient of the biological tissues. One of the effective parameters for changing the capacitance is dielectric coefficient which is used for distinguishing of different tissues [16].

2. Design Theory

Different geometries can be considered for constructing the capacitor but calculation of capacitance will be easier if a simple geometry is used. Therefore, the constructed capacitive sensor has been designed with parallel plates. In a pair of parallel plates which the distance between them is less than their own thickness, available electrical field between these plates is steady and has a parallel line shape. In this situation the effect of plates edges is ignored. Therefore, capacitance can be calculated from (1):

$$c = \frac{\varepsilon A}{d}, \tag{1}$$

In this equation, c is the capacitance (F), ε is the dielectric coefficient of the substance which is located between plates (F/m), A is the effective surface of plates or electrodes (m^2), and finally d is the distance between the two electrodes (m) [17], [18].

A. Force and its effect on capacitive changes in a sensor

Parameters which are important in normal and shear force measurement in the capacitive sensors are:

1. Spacing variation: Capacitance has an inverse relation with the distance between electrodes. Therefore, capacitance will be increased as the distance decreases. It is important that the plates do not move horizontally when the distance is changed. In other words, the effective surface should not be changed. Fig. 1 shows the effect of distance between electrodes on the capacitance.
2. Area variation: When two plates move horizontally relative to each other, the effective area will be changed and capacitance changes with area linearly. This parameter can be used for shear force measurement. The relation between changes of electrodes effective area and capacitance is shown in Fig. 2.

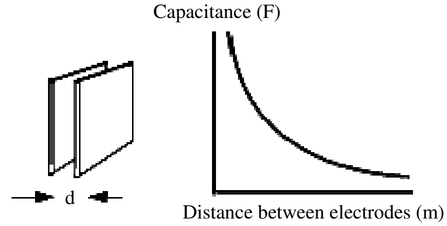

Figure 1: Effect of the changes the distance between electrodes on the capacitance [19], [20].

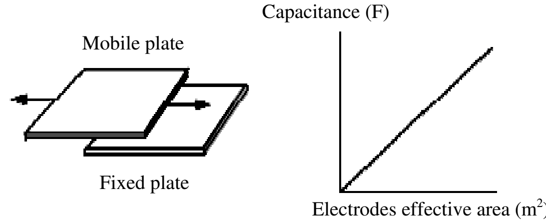

Figure 2: Effect of the changes the electrodes effective area on the capacitance [19], [20].

B. Specifications of designed and constructed sensor

This sensor is constructed with two cuprous plates of 9cm×9cm area and 2mm thickness. Elastic insulator foam of 3cm thickness and 4F/m dielectric coefficient is used in between. It is important to select a proper dielectric substance which returns to its initial position as the force is removed. Fig. 3 shows the constructed capacitive sensor.

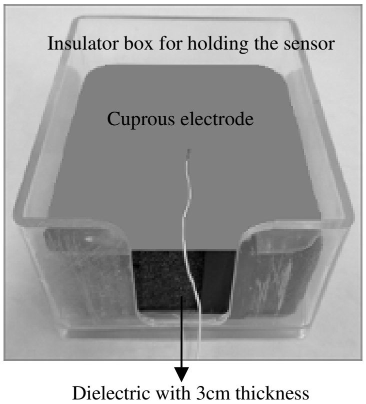

Figure 3: Constructed sensor.

Timer 555 is used in ASTABLE and MONOSTABLE designed circuits. Trigger base of timer 555 receives input pulse in MONOSTABLE circuit and this is the main difference between the two designed circuits. In fact, the advantage of trigger base existence is that the system will operate in a certain frequency. ASTABLE and MONOSTABLE circuits are designed in ORCAD using timer 555 shown in Fig. 4 and Fig. 5.

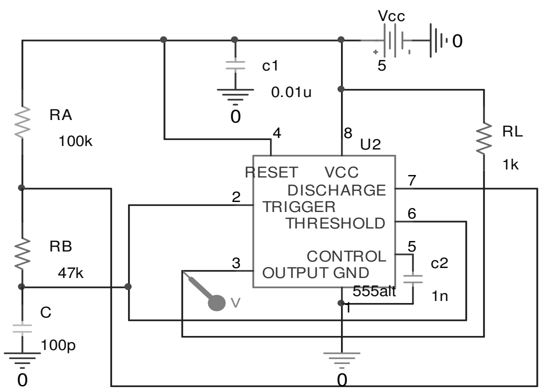

Figure 4: Designed ASTABLE circuit in ORCAD.

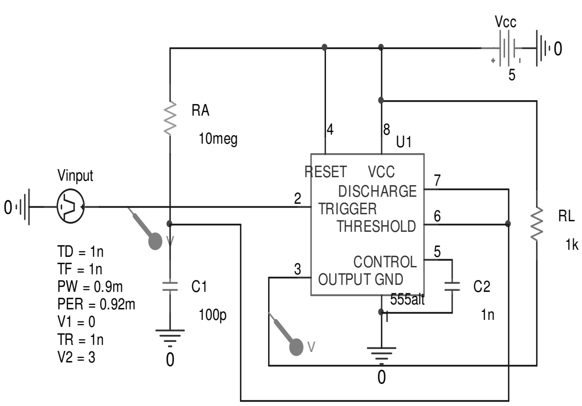

Figure 5: Designed MONOSTABLE circuit in ORCAD.

In these circuits variable capacitors are shown with c and c_1 changing in the range of 10pF-100pF. At first, two circuits are designed in ORCAD. Resistances which have been used in the designed ASTABLE circuit (R_A, R_B) have been determined according to the range of capacitance changes for reaching the accurate output. Resulting capacitance was measured through inserting certain amounts of force on the sensor (0.5kg-4.5kg). The resistances are equal to R_A=100kΩ and R_B=47kΩ. Also, the proper resistance (R_A) and input pulse in trigger base of timer 555 were determined in designed MONOSTABLE circuit then the outputs were registered with setting variable capacitance. Proper resistance was calculated as R_A=10MΩ and input square pulse includes period of 0.92ms with 0.02ms for lower voltage and -3V for voltage amplitude in MONOSTABLE circuit.

Then the designed ASTABLE and MONOSTABLE circuits were constructed on the bread board using electronic elements. Outputs were measured via oscilloscope and multi-meter in the form of frequency and time of upper voltage in ASTABLE and MONOSTABLE designed circuits, respectively. These circuits were constructed again on the printed circuits in order to decrease the error due to electronic elements movement. Fig. 6 and Fig. 7 show the ASTABLE and MONOSTABLE printed circuits.

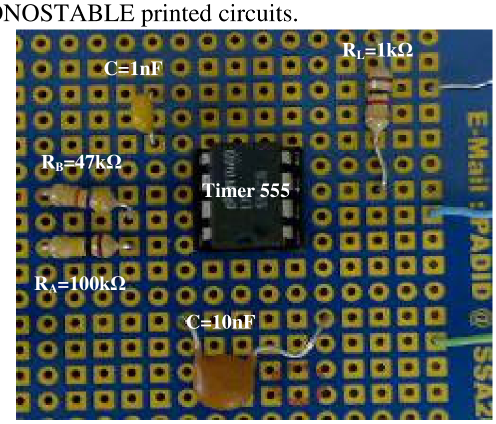

Figure 6: ASTABLE printed circuit.

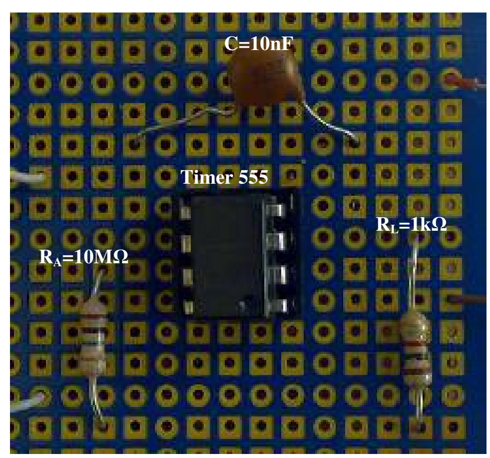

Figure 7: MONOSTABLE printed circuit.

Constructed capacitive sensor was tested in ASTABLE and MONOSTABLE circuits. Capacitance changes due to application of certain forces in the range of 0.5kg-4.5kg forces and the resulting outputs in the form of frequency and time have were registered in ASTABLE and MONOSTABLE circuits, respectively. Equipment used for measuring the outputs are shown in Fig. 8.

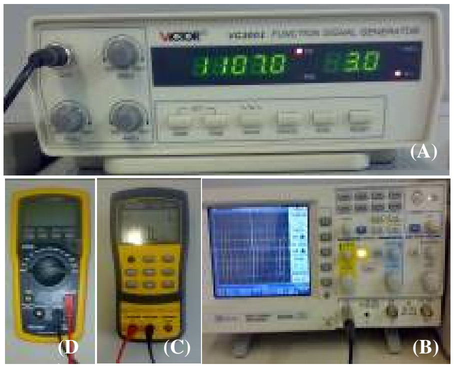

Figure 8: (A). Signal generator, (B). Oscilloscope, (C). LCR meter, (D). Multi-meter.

Signal generator in Fig. (8-A) is used for producing square pulse with certain amplitude and frequency. The oscilloscope shown in Fig. (8-B) is used for measuring output pulse in MONOSTABLE circuit. The LCR meter in Fig. (8-C) is used for measuring the constructed sensor's capacitance after applying a certain force and the multi-meter shown in Fig. (8-D) is used for measuring the output frequency in ASTABLE circuit.

3. Results And Discussion

A. Output of ASTABLE and MONOSTABLE circuits in ORCAD

The nonlinear relation between output frequency and capacitance changes in ASTABLE circuit is shown in Fig. 9. The range of capacitance is selected with a linear relation to frequency (42.6pF-51.5pF) for testing sensor operation. The relation between capacitance changes and time of upper voltage in MONOSTABLE circuit is direct. In this circuit, the range of capacitance is selected with a linear relation to time (31.6pF-40.5pF) for testing sensor operation.

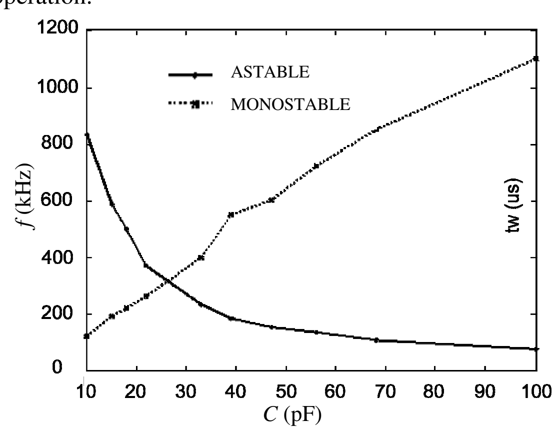

Figure 9: Output of ASTABLE and MONOSTABLE circuits according to the capacitance changes in ORCAD.

B. Output of ASTABLE and MONOSTABLE circuits with the use of variable capacitor

Comparing the data gained from ASTABLE and MONOSTABLE circuits in ORCAD and the experimental data gained via using variable capacitance in the constructed circuits shows that the capacitance less than 40pF in ASTABLE circuit and less than 30pF in MONOSTABLE circuit will produce noticeable error (Fig. 10).

In order to solve this problem and eliminating the resulting error, a 33pF capacitor is used in parallel with constructed sensor in ASTABLE circuit and a 22pF capacitor is used in parallel with this sensor in MONOSTABLE circuit. These capacitances are calculated according to the range of capacitance exhibiting linear behavior with respect to the output until the difference between data gained from ORCAD and experiment decreases.

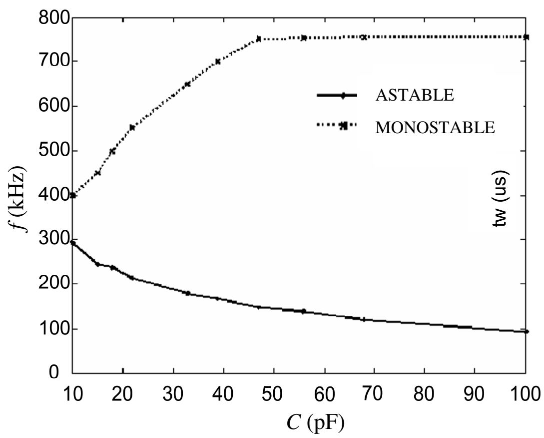

Figure 10: Output of ASTABLE and MONOSTABLE circuits according to the capacitance changes with using variable capacitor.

C. Output of ASTABLE and MONOSTABLE circuits with using constructed sensor

Sensitivity of this sensor is 500gr due to the gained outputs, material of insulator foam and its mechanical specifications. Therefore, applying a force less than this value does not change the distance between electrodes of the constructed sensor. A spongy dielectric substance can be used in this sensor for having more sensitivity. Data gathered from the constructed sensor in two ASTABLE and MONOSTABLE circuits are presented in Table (1).

TABLE 1
DATA GATHERING FROM CONSTRUCTED SENSOR

C (pF)	m (kg)	ASTABLE circuit f (kHz)	MONOSTABLE circuit t_w (ms)
9.6	0	164	0.575
9.8	0.5	162	0.6
10.1	1	160	0.625
10.5	1.5	157	0.65
11.1	2	155	0.675
12	2.5	150	0.7
13.8	3	146	0.725
15.2	3.5	143	0.75
16.4	4	139	0.775
18.5	4.5	137	0.8

D. Output of ASTABLE and MONOSTABLE circuits with using analysis solution

Output frequency can be calculated from (2) in ASTABLE circuit. In this equation, R_A and R_B are the resistances (Ω) used in this circuit, C is capacitance (F), and f is the output frequency (Hz).

$$f = \frac{1.45}{(R_A + 2R_B)C} \quad (2)$$

Time of upper voltage can be determined from (3) in MONOSTABLE circuit. In this equation, t_w is time of upper voltage, R_A is resistance (Ω) which is used in this circuit, and C is capacitance (F).

$$t_w = 1.1 \times R_A C \quad (3)$$

As explained before when a certain force is imposed on the constructed sensor the capacitance will be changed in ASTABLE circuit so the output frequency can be measured in this circuit. The capacitance is calculated from (4) in which x is the distance between two capacitor plates (m).

$$C = \frac{\varepsilon_0 \varepsilon_r A}{x} \quad (4)$$

Parameter x can be calculated from (5) considering linear elastic behavior for the dielectric substance.

$$x = \frac{\varepsilon_0 \varepsilon_r A \times (R_A + 2R_B) f}{1.45} \quad (5)$$

Therefore, the inserted force on the constructed sensor will be calculated considering the output frequency as follows in (6).

$$F = kx \rightarrow F = \frac{\varepsilon_0 \varepsilon_r A \times (R_A + 2R_B) k}{1.45} \times f \quad (6)$$

Comparing the data obtained from formulas and the data gathered from simulation in ASTABLE and MONOSTABLE circuits show error of 5.5%. Fig. 11 and Fig. 12 show the data gathered from simulation and analysis solution in ASTABLE and MONOSTABLE circuits, respectively.

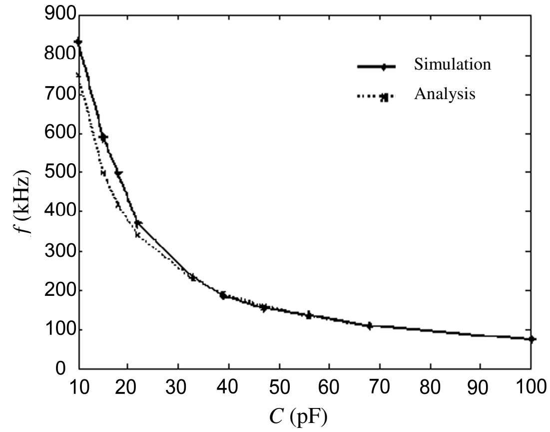

Figure 11: Comparing results of simulation and analysis solution in ASTABLE circuit.

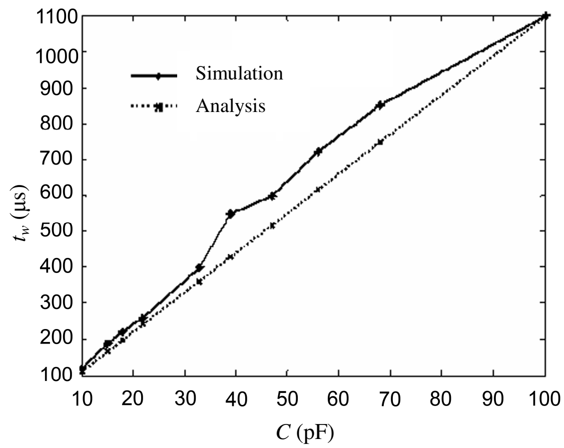

Figure 12: Comparing results of simulation and analysis solution in MONOSTABLE circuit.

Data gained from variable capacitor, simulation in ORCAD, and analysis solution methods have an error of 5.5%. Fig. 13 and Fig. 14 show the data gathered from constructed sensor and analysis solution in ASTABLE and MONOSTABLE circuits, respectively.

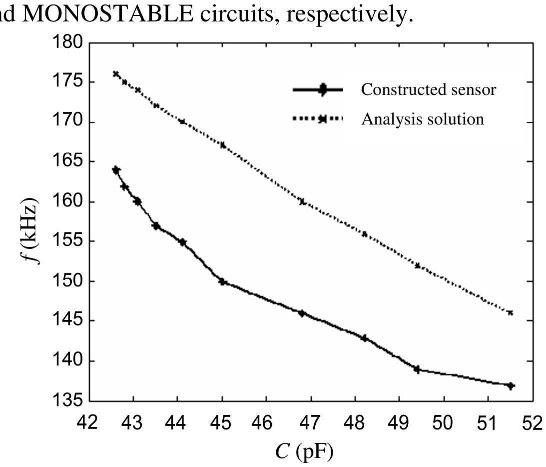

Figure 13: Comparing results of constructed sensor and analysis solution in ASTABLE circuit.

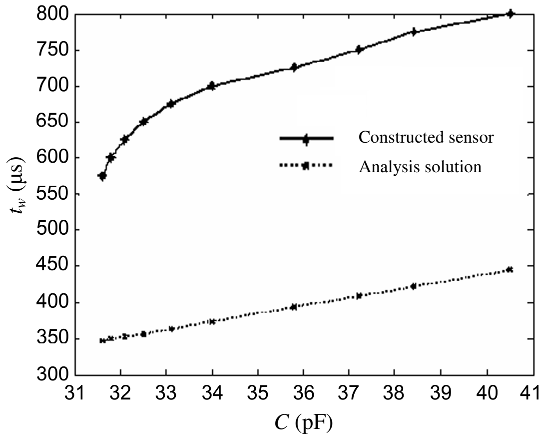

Figure 14: Comparing results of constructed sensor and analysis solution in MONOSTABLE circuit.

All the points shown in Fig. 13 and Fig. 14 depict the same amount of error between the results gathered from constructed sensor and analysis solution in two ASTABLE and MONOSTABLE circuits. In other words, error can be decreased by adding a constant parameter to the results of constructed sensor in the ASTABLE circuit and subtracting a constant parameter from the results of constructed sensor in the MONOSTABLE circuit. It can be used for showing the output in digital form.

According to the results, the constructed sensor has less error in the ASTABLE circuit compared to the MONOSTABLE circuit. Besides, the results obtained from the ASTABLE circuit have more clarity. In the case of similar outputs from the MONOSTABLE circuit, the reading errors of these values are increased. So, the ASTABLE circuit is more efficient for the proposed capacitive sensor. Outputs of ASTABLE circuit have more severability and it is more useful for smaller capacitive sensors. Presented capacitive sensor has repeatability after several forcing.

One of the main goals in this research is evaluation of the capacitive performance for using robotics in the field of medicine. We tend to design smaller circuit for the purpose of smart surgical instruments, with increased sensor sensitivity and decreased amount of energy consumption.

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