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Chapter

Electromechanical Analysis (MEMS) of a Capacitive Pressure Sensor of a Neuromate Robot Probe

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Abstract

The domain of medicine, especially neurosurgery, is very concerned in the integration of robots in many procedures. In this work, we are interested in the Neuromate robot. The latter uses the procedure of stereotaxic surgery but with better planning, greater precision and simpler execution. The Neuromate robot allows in particular the registration with intraoperative images (ventriculographies, and especially angiographies) in order to perfect the planning. In this book, we focus on the contact force measurement system required for the effectiveness of the stimulation between the robot probe and the patient's head and thus ensure the safety of the patient. A force sensor is integrated upstream of the wrist, the pressure sensor is part of a silicon matrix that has been bonded to a metal plate at 70°C. The study was carried out under the software COMSOL Multiphysics, ideally suited for the simulation of applications (Microelectromechanical systems) "MEMS". After electromechanical stationary survey, deflection of the quadrant when the pressure difference across the membrane was 25 kPa, as expected, the deviation was expected to be greatest at the center of the membrane. The proposed sensor structure is a suitable selection for MEMS capacitive pressure sensors.

Keywords: medical robotics, neuromate robot, capacitive pressure sensor, COMSOL, MEMS

1. Introduction

In the past half-century, the Neurosurgery has been undergone tremendous technological innovation. The introduction of the operating microscope, stereotactic surgery, neuro endoscopy, modern neuroimaging, technologically demanding implants and image-guided surgery have enabled advancements while also challenging the limits of human dexterity [1]. Robot-assisted surgical systems can be beneficial for a variety of procedures chirurgical cranial and orthopedic due to their high precision, and ability to access and capacity to integrate various imaging and sensing modalities into the execution of the surgical task [2, 3].

The robot assisted surgical such Neuromate robots helps to ensure that the burr hole is accurately positioned and oriented cantered on the trajectory axis. The trajectory orientation is not restricted due to the variety of configurations to guide the surgery tools with a suitable orientation [4]. The current system (see **Figure 1**) consists of the following major components: a modified Neuromate robot.
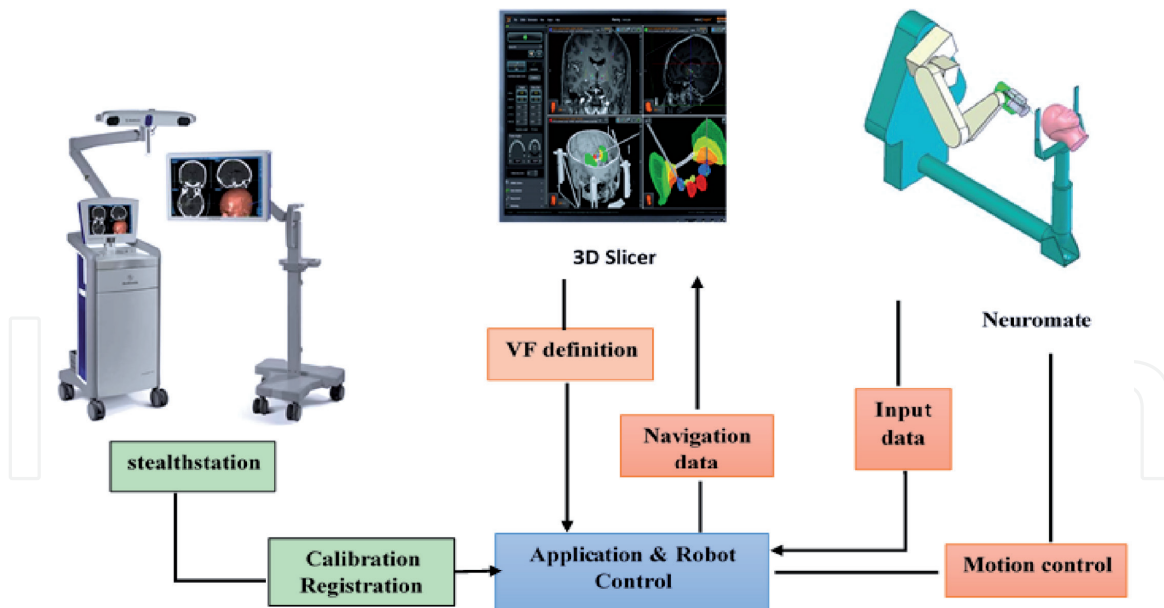
Figure 1.
System overview of the image-guided robot for skull base surgery [1].

Since the evolution of Micro-electro-mechanical systems (MEMS) many types of MEMS pressure sensors have been notified. They can be divided MEMS pressure sensors into, capacitive [5], piezoresistive [6], resonant [7]. Capacitive pressure sensing is considered as one of the most sensitive techniques in detecting low pressures [8]. Owing to the fact that the performance is solely a function of the mechanical properties and dimensions of the sensor structure [9]. Capacitive pressure sensors are preferred as they provide high sensitivity to pressure and their performance for most part remains invariant of temperature, this makes it suitable to be used for high pressure and temperature applications [10, 11].

This work addresses the design and modeling of measurement system required the contact force for the effectiveness of the stimulation between the probe and the patient's head, thus ensuring the safety of the patient. However, capacitive pressure sensors are gaining market share over their piezoresistive counterparts since they consume less power, are usually less temperature sensitive and have a lower fundamental noise floor. This model performs an analysis of a capacitive pressure sensors as discussed below using the electro mechanics interface. The effect of a rather poor choice of packaging solution on the performance of the sensor is also considered. The results emphasize the importance of considering packaging in the MEMS (micro-electro mechanical system) design process (**Figure 1**).

2. Neuromate robotic device and surgical procedure

Stereotactic biopsy is a standard procedure in neurosurgery. In addition to or even replacing frame based stereotaxy, some centers also use frameless imaging-based techniques and more recently robotic systems. Here, Yasin et al. [12] report a retrospective analysis of experience with 102 consecutive biopsies performed in his institution using the Neuromate robotic device.

The Neuromate robotic device is a platform designed for robot assisted stereotactic neurosurgery. It consists of a robotic arm with 5 degrees of freedom and a planning station (**Figure 2A**) and can be used for frame-based surgery as well as in frameless mode.

The Neuromate device has been employed for a wide variety of stereotactic applications in neuro endoscopy, biopsy, epilepsy surgery, functional neurosurgery, and even convection-enhanced delivery.
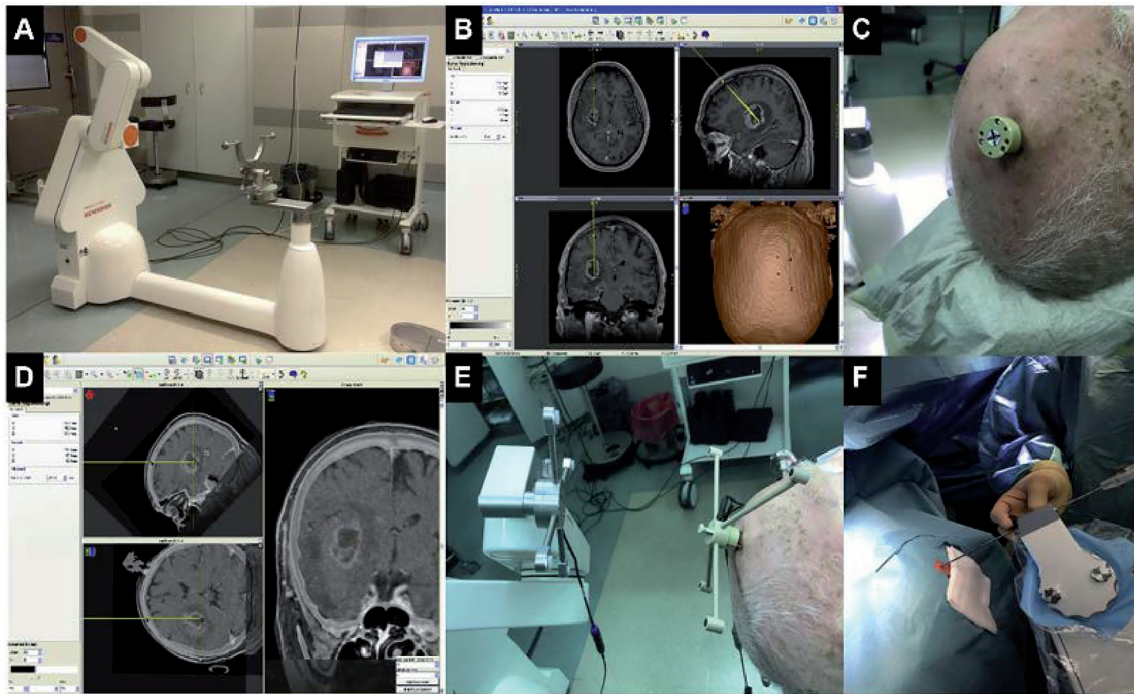
Figure 2.
Images of the Neuromate robot and surgical workflow [12]. (A) Robot and planning station. (B) Trajectory plan. (C) The base of the localizing device is mounted to the skull. (D) The preoperative magnetic resonance imaging including the trajectory is fused to the computed tomography reference scan. (E) Patient registration using the ultrasonic tracking system. (F) Positioning the biopsy needle through the instrument holder along the trajectory [12].

All patients included in his study [12] had frameless biopsies. Biopsy trajectories were planned in advance using VoXim neuromata software (**Figure 2B**).

The localizing device consisted of a base mounted to the skull using a bone screw under local anesthesia and a helicopter-shaped ultrasonic localizing device and corresponding computed tomography (CT) localizers (**Figure 2C**). A CT reference scan was obtained and the data were uploaded on the planning station.

Next, the biopsy trajectory and the preoperative MR scan were fused to the reference scan (**Figure 2D**). Verifying trajectories were planned based on the reference scan data.

The second part of the procedure was performed in all patients under general anesthesia. Patients were placed in the supine, lateral, or prone position as required. The head was fixed in the head holder of the robot with 4–6 pins. Patient registration was performed using the ultrasound tracking system (**Figure 2E**).

Accuracy was tested using the verifying trajectory and a laser pointer mounted to the robot.

Next, the robotic arm with the instrument holder was moved into the planned biopsy position using a remote control. A Sedan side cutting aspiration needle (1.8 mm) was introduced manually through the instrument holder, and standard serial biopsies were taken as indicated (**Figure 2F**).

Biopsies through separate trajectories were obtained after simply repositioning the robotic arm.

3. Configuration of the neuromate robot

Nowadays, the use of robots in medicine becomes usual. One of the problems widely dealt in this area is the trajectory planning and contact force control.

In Menasria et al.'s (2015) works [13], a novel trajectory planning approach is proposed for redundant manipulators in the case of several obstacles. They use the
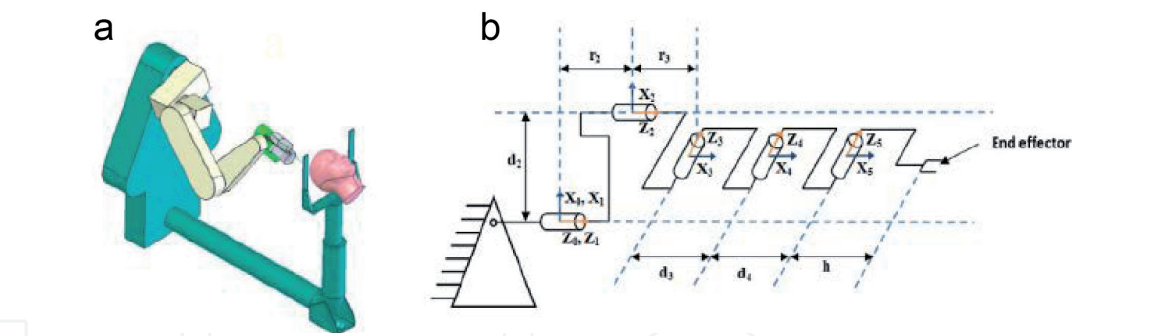
Figure 3.
The Neuromate robot [13]. (a) Representation of the robot. (b) Geometric configuration of the robot.

property to find the best configuration that allows to avoid obstacles and singularities of the robot. The proposed method is based on a bi-level optimization formulation of the problem and bi-genetic algorithm to solve it.

The Neuromate robotic device is a platform designed for robot assisted stereotactic neurosurgery. It consists of a robotic arm with 5 degrees of freedom and a planning station (**Figure 3**) and can be used for frame-based surgery as well as in frameless mode. The Neuromate device has been employed for a wide variety of stereotactic applications in neuro endoscopy, biopsy, epilepsy surgery, functional neurosurgery, and even convection-enhanced delivery. Next, the assigned coordinate frames are followed to fill out the parameters as shown in **Tables 1** and **2** below.

Geometric and kinematic modeling was carried out under the symbolic software MapleSim (**Figure 4**) in order to simulate the trajectory of the probe.

3.1 Neuromate inverse kinematics analysis

Numerically, Inverse kinematic analysis is done by multiplying each inverse matrix of T matrices on the left side of above equation and then equalizing the corresponding elements of the equal matrices of both ends.

DH parameters	T_0^1	T_1^2	T_2^3	T_3^4	T_4^5
d_i	0	d_2	0	d_4	d_5
d	0	0	r_3	0	0
r_i	0	r_2	r_3	0	0
θ_i	θ_1	θ_2	θ_3	θ_4	θ_5

Table 1.
Denavit Hartenberg table of the robot [13].

Joints	Mint (rad)	Max (rad)
θ_1	$-\pi$	π
θ_2	$-\pi$	π
θ_3	$-\pi/2$	$\pi/2$
θ_4	$-\pi/2$	$\pi/2$
θ_5	$-\pi/2$	$\pi/2$

Table 2.
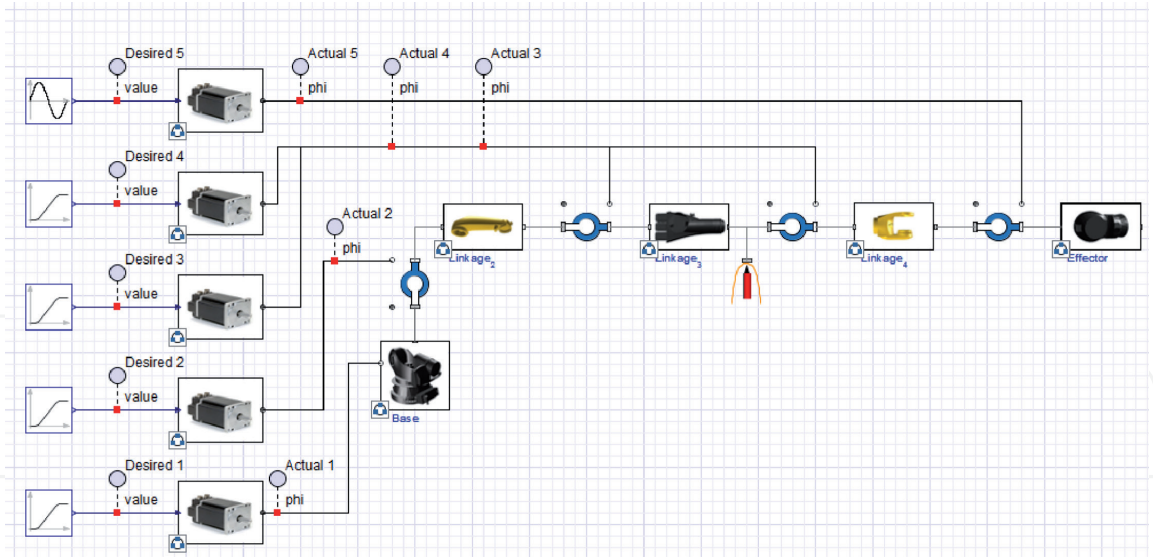*Angular rangers of the rotary articulations [13].*

Figure 4.
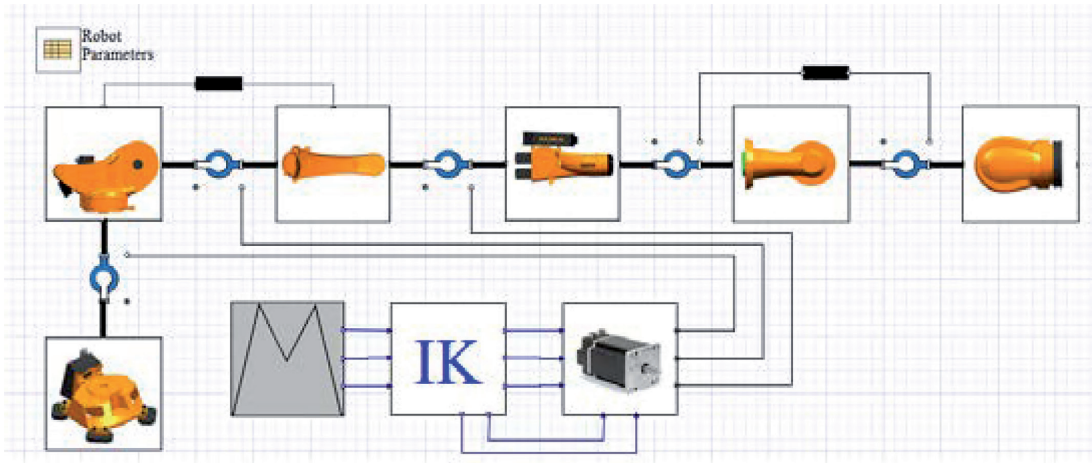*Modelization of the Neuromate robot in MapleSim.*

Figure 5.
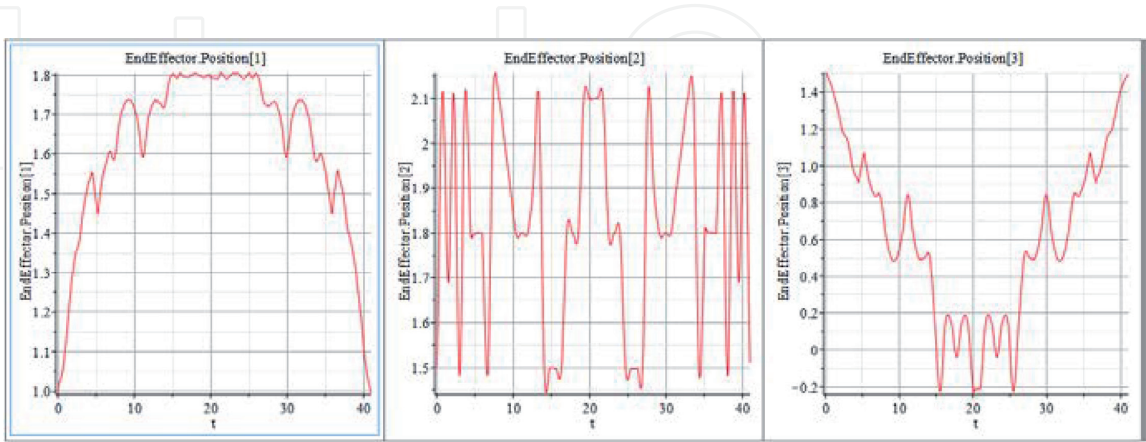*Inverse kinematics of the Neuromate robot in MapleSim.*

Figure 6.
End effector positions of the Neuromate robot.

With inverse kinematic solutions, the value of each joint can be determined in order to place the arm at a desired position and orientation. In our case, inverse kinematics is done under MapleSim software (**Figure 5**).

Based on relevant theories on robotic arms movement, a forward and an inverse kinematic model are successfully developed with the application of Neuromate with 5 dof in MapleSim software.

A simple trajectory is carried out in order to investigate the forward and inverse kinematics models of Neuromate. A movement flow planning is designed and further developed into the MapleSim programming.

A summary of the calculation is obtained for tree position of end effector (**Figure 6**).

4. Robotic pressure sensor control

In robotic applications, position control of manipulators can only be effective if the task is precisely described. For this reason, there is a clear need to integrate force information to the control loop. The interaction control between the effector and the patient's head can be through the robot's position control algorithms in the direction of the task space while the environment imposes natural position constraints.

Pressure control has many advantages. It can provide the necessary Cartesian compliant behavior of a robot, enable robust and fast manipulation in contact with unknown surfaces, and provide safety and dependability in interaction with humans.

Surgical robots with pressure control the pressure information collected in one of the above described ways may be used to control the servos of the robot. In medical robotics, the fundamental methods of force control have been widely applied as usually there is interaction with patient, interaction with surgeon and the procedures mostly deal with soft and deformable tissues with variable stiffness. The realized control architecture can depend on the bandwidth of the force sensor (the frequency of sensor measurements) [14–16].

The following section presents an example of the field of surgical robotics performing pressure control by a force control MEMS probe described above.

5. Geometry and material properties of pressure sensor

Newly Micro electro mechanical system (MEMS) capacitive pressure sensor gains more advantage over micro machined piezo resistive pressure sensor due to high sensitivity, low power consumption, free from temperature effects, etc.

Geometry of Pressure sensor made of piezoelectric silicon layer and graphene substrate at 70°C, with high-pressure sensitivity of 120 pF/Pa.

Since the geometry is symmetric, only a single quadrant of the geometry needs to be included in the model, and it is possible to use symmetry boundary condition. **Figure** 7 shows the total sensor geometry.

As extensively reported in Mechanics books and scientific papers, the governing differential equation for the deflection of a thin plate in Cartesian coordinates can be expressed as follows:

$$\Delta C = C - C_0 = \varepsilon A \frac{\Delta d}{d(d - \Delta d)} \tag{1}$$

D is referred as the flexural rigidity of the plate and can be defined as follows:

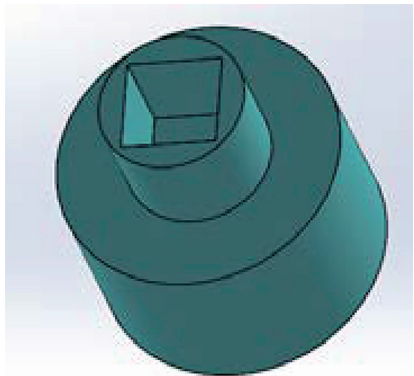$$D = \frac{E t_m^3}{12(1 - \upsilon^2)} \tag{2}$$

Figure 7.
The geometry of the total sensor.

With E and v being the modulus of elasticity and Poisson's ratio of the plate material, respectively.

The mechanical deformation under compression for the pressure sensitivity of such a pressure sensor:

$$\Delta C = C - C_0 = \varepsilon A \frac{\Delta d}{d(d - \Delta d)} \tag{3}$$

ΔC is the charge of capacitance under compression, C_0 is the initial capacitance value the sensor, A is the surface area of the overlapping plates, ε is the permittivity of dielectric medium between the two plates, d is the initial overall thickness of the medium and Δd is the amount compression.

The designed MEMS capacitive pressure sensors are composed of a square silicon diaphragm of 500 μm side length and 500 μm thickness that deflects because of pressure and acts as the movable plate of a differential capacitor, and a fixed Graphene substrate that acts as the other half of the pressure dependent capacitor.

5.1 Mechanical properties

The property material of graphene and Silicon is defined into the model is shown in **Table 3**.

	Symbol	Silicon	Graphene
Young's modulus (GPa)	E	170	1000
Poisson's ratio	v	0.6	0.17
Density (Kgm^{-3})	ρ	2330	2000
Relative permittivity	ε	11.7	2.14
Coefficient of thermal expansion (1/K)		2.6e-6	8e-6

Table 3.
Material constants for silicon and graphene.

6. Results and discussion

The deformation surface of the membrane when a pressure of 25 kPa is applied to it, in the absence of packaging stresses, the maximum deflection is 3.64×10^{-8} m and the minimum deflection is 2.58×10^{-8} m (**Figure 8**).
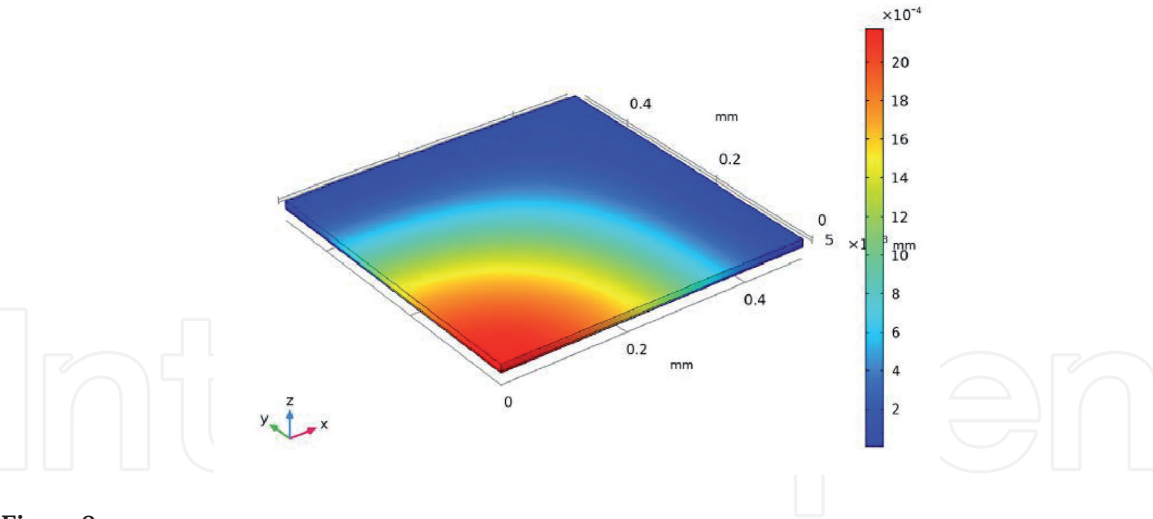
Figure 8.
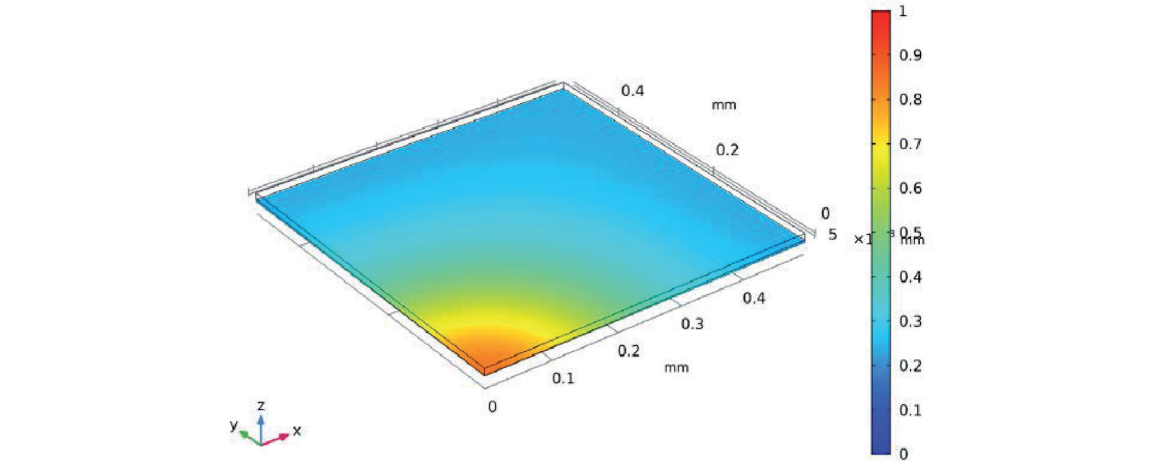*Surface of the deformation membrane when applied voltage is 25 kPa.*

Figure 9.
Electric potential in the sealed chamber, plotted on a slice between the two plates of the capacitor.
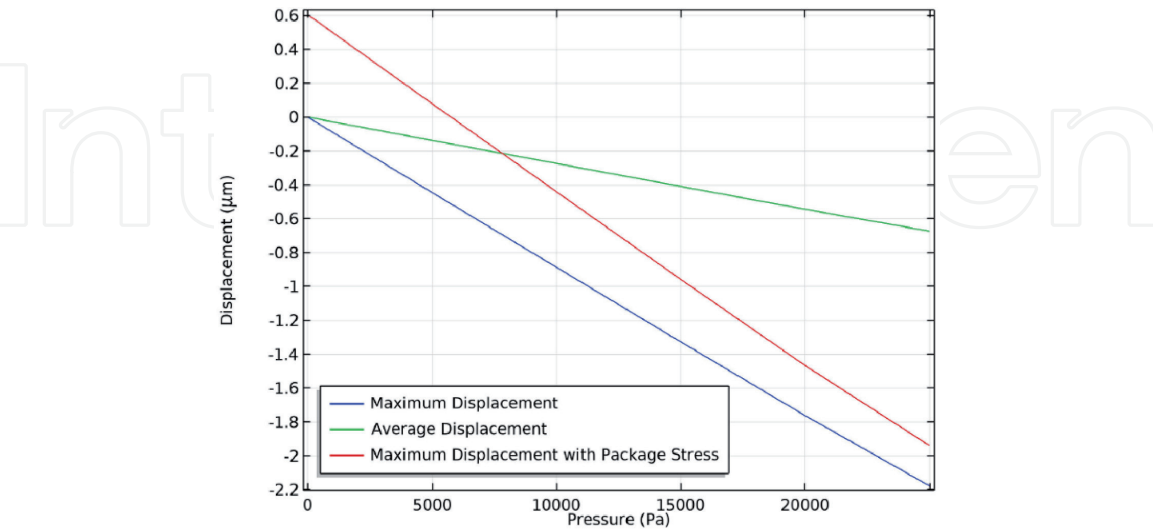

Figure 10.
Displacement of the membrane as a function of the applied pressure.

Figure 9 shows the surface potential on a plane located between the plates. The potential is almost uniform and the value is near to 0.3 V.
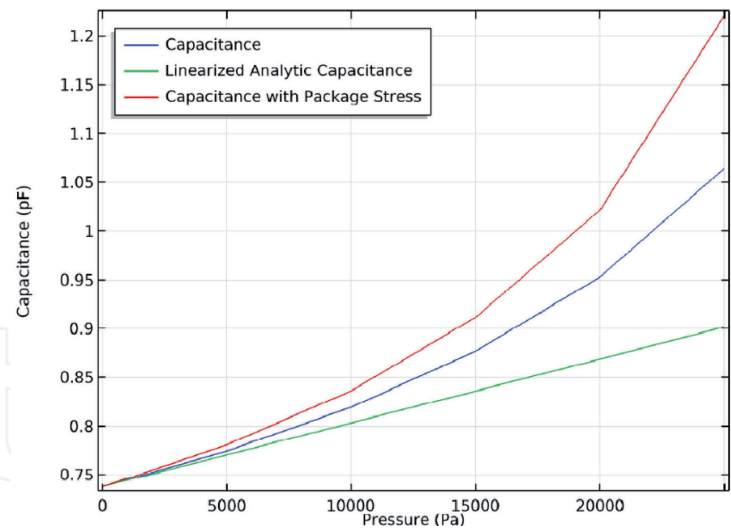
Figure 11.
Capacitance of the membrane as a function of applied pressure.

In **Figure 10**, the simulated median and maximum displacements of the membrane as a function of applied pressure. At an applied pressure of 10 kPa, the diaphragm displacement in the center is 0.15 μm. The mean displacement of the diaphragm is 0.5 μm. These results indicate the mean diaphragm and the maximum diaphragm results are very close which increases the stability of the sensor.

Figure 11 shows that the capacitance of the device increases nonlinearly with applied pressure.

At zero applied pressure the sensitivity of the model (quarter of the whole sensor) is 7.4×10^{-6} pF/Pa. The device sensitivity is therefore 7.4×10^{-6} pF/Pa.

The capacitance without package stress is less than the analytic capacitance but the capacitance with package stress is greater than the analytic capacitance.

7. Conclusion

In this work, a symbolic modeling under MapleSim is presented for the purpose of trajectory generation. In addition, we presented a simulation and analysis of the MEMS capacitive pressure sensor for robot Neuromate probe using COMSOL Multiphysics. The results show that the slotted MEMS capacitive pressure sensor realizes good sensitivity and large operating pressure range. Furthermore, as the ease of designing and fabricating these devices continues to improve, researchers will increasingly turn towards MEMS as standard tools for Neurosurgery.

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