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Characterisation of Conductive Polymer for EIT based Sensor

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Abstract **-** The development of an artificial skin interface would add the sense of touch to the rapidly developing field of robotics. This added capability would significantly enhance the interactive aptitude of humanoid and bipedal robots and accelerate their adoption in more productive environments. Despite the vast variety of tactile sensors currently available, their integration over complex geometries remains deterred by their stiff and un-stretchable nature attributed to the presence of a wire mesh within the sensing area. Eliminating the need for wires within the pressure sensing area will significantly enhance the flexibility and stretch capabilities of resistive tactile sensors. An Electrical Impedance Tomography (EIT) based pressure sensor can acquire the pressure profile from a conductive sheet by limiting electrodes only to its boundary, hence allowing for a simpler stretchable artificial skin interface. In this paper, we characterise the use of the conductive polymer CS57-7RSC as an Electrical Impedance Tomography (EIT) based pressure sensor. Sensor development and the EIT system configuration are highlighted. In addition, corresponding test protocols and evaluation methods are introduced. With electrodes placed only at the boundary of the sensing area, the relationship between pressure and change in conductivity is validated using normal loading experiments. Sensor calibration is performed and the resolution and position error are selected as the primary means to objectively quantify the performance of the sensor. Moreover, the quality of the reconstructed images is investigated and the nonlinear relationship between pressure and relative change in conductivity is validated using experimental data.

Keywords**:** Electrical impedance tomography, Pressure sensing, Artificial skin, Tactile sensing

1. Introduction

Robots with enhanced human robotic interaction capabilities are crucial to their integration in homes, industrial and health care facilities. The concept of an artificial pressure sensitive skin that is capable of distinguishing multi-touch stimuli in addition to detecting pressure is key to the field of human-robotic interactions. Tactile sensor technology based on resistive sensors which include: micro-machined strain gauges, conductive elastomers, conductive polymers and fluids are most common. Capacitive sensors as well as optical sensors are also very effective alternatives, the reader is referred to (Yousef *et al*. 2011) for a more comprehensive review of tactile sensors used for robotic interactions. Despite the large variety of sensors that are currently available, their adoption in the field of humanoids and bipedal robots is restricted due to their stiff nature and minimal flexibility caused by the physical structure of the sensor. This limitation is typically caused by the presence of a wire mesh in the contact area of the sensor. Electrical Impedance Tomography (EIT) based pressure sensitive skin has the potential to cover areas such as joints in addition to ground reaction force measurement for foot sensing, giving a single complete sensing solution. EIT is primarily a medical imaging technique used to find the conductivity distribution within the body by placing electrodes only at the boundary of the conductive volume. As such, numerous industrial applications ranging from image reconstruction of gas/solid fluid flow within piping to geophysics (Holder, 2005) have adopted this technology. EIT based pressure sensing was initially introduced by (Fulton and

Lipczynski, 1993) for measuring body support pressure distribution in order to aid in reducing bed sores. However, the experimental trials failed to identify a suitable conductive material for the EIT pressure sensor. In addition, taking advantage of the enhanced flexibility and stretch potential of the EIT sensor was not considered. Further work has been conducted recently by (Alirezaei *et al*. 2007) where emphasis was on the flexibility and stretch potential of these sensors and their integration in robotics as an artificial skin interface. Promising results were depicted but no performance measures were established to analyze the capability of the sensor to detect pressure and how accurately it can reconstruct the pressure profile. (Tawil *et al*. 2011) focused on comparing alternative algorithms in order to enhance image reconstruction for the EIT pressure sensing application. Their forward model used for image reconstruction did not include a complete electrode model and there was no investigation of the pressure and conductivity change relationship.

The challenge of implementing an EIT pressure sensing solution is in the selection of the materials, the hardware platform used for raw data acquisition and the model used for image reconstruction. Moreover it is necessary to systematically establish a means to quantify the quality of the reproduced images and characterize their ability to depict the pressure profile. In this paper we developed and characterized an EIT based pressure sensor using Pressure Sensitive and Conductive Rubber (PSCR) material CS57-7RSC (PCR technical, Japan). An experimental apparatus is setup for normal pressure trials and a calibration curve is established. Moreover the resolution and position error are examined as a function of the location of the stimulated area. Section 3 introduces the methodology used to analyze our sensor in detail. The hardware, material properties based on preliminary testing, and corresponding EIT model used in the design is covered in section 4. Section 5 presents our experimental results along with our performance measures which characterize the effectiveness of our EIT pressure sensor followed by the conclusion in section 6.

2. Methodology

In order to characterise the performance of the EIT pressure sensor two experiments were performed. The purpose of which is to quantify the ability to detect pressure and the effectiveness of which a pressure profile can be obtained over the entire sensing area. The sensor functioned by first acquiring no load reference voltage data given an adjacent current stimulation and measurement pattern. Data is then compared to this reference state that is only set once at the beginning of both experiments

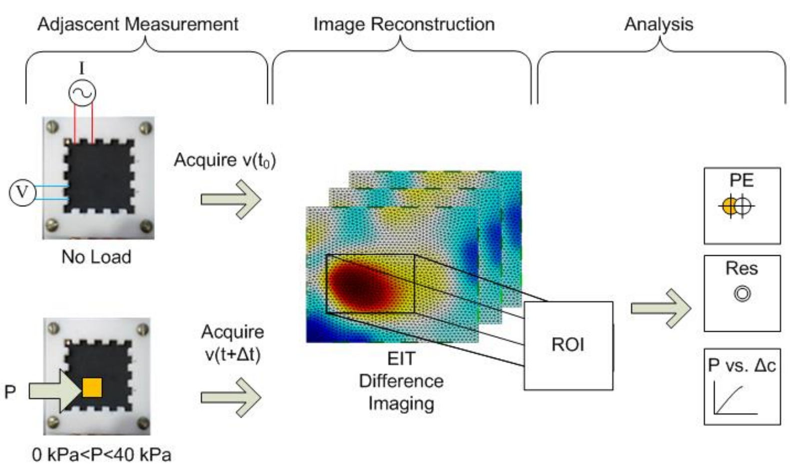


Fig. 1. EIT based pressure sensor overview

Primarily, pressure was varied at a fixed location in order to establish the relationship between pressure and conductivity change. Secondly, the load applied was fixed and the location of the stimulated region was varied over the entire sensing surface. The EIT sensor’s reconstructed images depict the relative conductivity change which is directly attributed to the pressure profile of the stimulus. In order to minimize the inclusion of image artefacts in our analysis a Region of Interest (ROI) is initially established. The cause of these artefacts can be attributed to noise, electrode movement and the EIT reconstruction method. Once the ROI is selected from the reconstructed images, the conductivity changes are analyzed as seen in **Error! Reference source not found.**. A maximum amplitude threshold is established and a ROI data set composed of pixels with values that are greater than quarter of the threshold are selected. After which the mean value of the ROI is used to conclude the conductivity change due to the applied pressure and establish the calibration curve. The Centre of Pressure (CoP) is also calculated based on the ROI where each pixel is weighed based on its conductivity value.

Position Error (PE) and Resolution (Res) are selected as the figures of merit used for image analysis. These figures of merit as defined in (Adler *et al*. 2009) and used for EIT system evaluation by (Maimaitijiang *et al*. 2011) give a quantifiable means to evaluate the performance of the sensors reconstructed images. The effect of stimulating an area with close proximity to the electrodes as opposed to the centre of the phantom is compared. Negative PE represents error in the position away from the centre where in Eq. (1) p_t is the position of the target and p_{CoP} is the position of the CoP of the ROI acquired from the sensor image. In Eq. (2), A_q and A_o are the sum of the amplitude of all the elements within the ROI and the entire image respectively.

$$\boldsymbol{PE} = p_{t-}p_{CoP} \quad (1)$$

$$\boldsymbol{Res} = \sqrt{\frac{Aq}{Ao}} \quad (2)$$

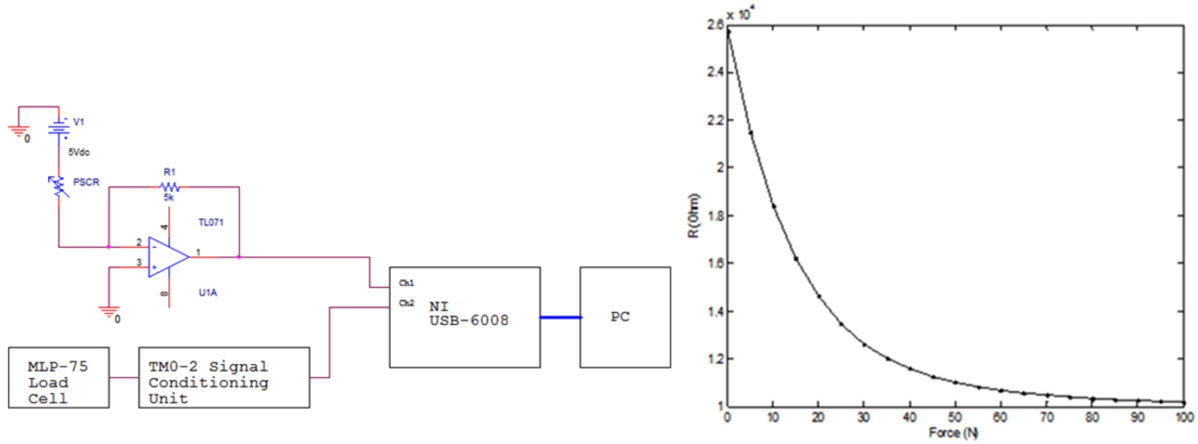
3. Design

Typically, PSCR materials have high resistance properties. Compressing a conductor onto such a PSCR sheet causes the resistance of the contact to fall with increasing pressure. The foundation of the EIT based artificial skin is to combine the ability to relate the pressure with the conductivity change and visualize the location of the stimulated area by only having the electrodes at the boundary. The developed sensor is composed of the PSCR sheet that is housed in a fixture which ensures constant electrode contact and position. Data acquisition is performed using the Sigma Tome II EIT system, along with its software platform Memtade (Ecole Polytechnique of Montreal, Canada). The adjacent current drive pattern is selected which involves injecting current, and grounding an adjacent pair of electrodes. A typical 16 electrode configuration, where the exciting probes are shifted by one electrode for each cycle, will collect a total of 208 voltage measurements. This set of voltage measurements is referred to as one frame. The EIT system was configured for difference imaging where sensor output depicts relative conductivity changes. A reference frame ($v(t_0)$) is initially acquired at a no load state. Subsequent frames ($v(t_0+\Delta t)$) are used in relation to the reference frame via the EIT difference imaging scheme.

Setting up and solving the ill-posed non linear EIT problem, in order to find the conductivity distribution within the PSCR, was achieved by using Electrical Impedance Tomography and Diffuse Optical Tomography Software (EIDORS). EIDORS is an open source software suite that runs over Matlab (Adler and Lionheart, 2006). The Finite Element Mesh used in the forward model was generated using Distmesh (Persson and Strang, 2004) which is integrated into EIDORS. Solving the inverse model and projecting the results on the mesh yields the sensors pressure image.

3. 1. Conductive Polymer Sample

CS57-7RSC often referred to in the literature as Pressure Sensitive Conductive Rubber (PSCR) was selected for this purpose. It is essentially composed of silicon rubber impregnated with carbon filler. It is important to note that the material in itself is not pressure sensitive. However, based on the analogy of contact impedance a resistance change is detected when pressure is applied directly on stacked setup where a conductive layer is compressed onto the material. The sensor characteristics and range rely extensively on the surface roughness of the PSCR sheet. The range is recognized according to the load value reached when 80 % of the nominal interface area of the electrode has come into contact with the conductive sheet (Weiss and Worn, 2005).



(a) (b)

Figure 2. (a) Schematic of data acquisition setup used to evaluate contact resistance relationship of PSCR for preliminary feasibility test, (b) Force/ Resistance relationship for PSCR sample using dual coplanar electrode setup

The relationship between pressure and resistance of the PSCR was characterized by conducting an initial preliminary experiment where a normal load was applied on a square shaped sample 5 cm^2 with coplanar copper electrodes placed on the bottom surface of the PSCR. The preliminary setup shown on Fig. 2:a was used for data acquisition prior to the EIT setup which involves a voltage divider circuit where the PSCR acts as a variable resistor. A non-linear regression analysis was performed using Matlab curve fitting toolbox and the relationship between Pressure and Resistance of the PSCR is shown in Fig. 2:b. The non linear decrement in resistance with the increased pressure, on the PSCR sample, yields an applicable range up to 35 kPa based on the force measurements.

3. 2. EIT Sensor Hardware Setup

The aim of our hardware setup is to mount boundary electrodes on the PSCR sample while maintaining a fixed flat surface area in order to objectively evaluate the materials performance in EIT sensing prior to its use in more complex geometries. The hardware is composed of two main parts: The EIT system and the fixture. The Sigma Tome II EIT system along with the Memtade software suite was used for data acquisition as seen in Fig. 3:a. AC current excitation is used and the scan-head can be configured for any custom stimulation and measurement patterns. For all the conducted trials voltage measurements were not acquired from the drive electrodes. A minimum of 20 frames were recorded for each load applied.

3. 2. 1. Fixture

The PSCR is manufactured in 0.5 mm sheets allowing for high flexibility. A fixture was designed in order to constrain the motion of the PSCR sample and fix the location of the electrodes. Motion artifacts are a major concern in EIT image reconstruction resulting from the undesirable movement of the electrodes during data collection (Webster, 2010). The fixture was manufactured using a 3D printer and was made of insulating thermoplastic. It is composed of two parts that are mounted on top of each other with the electrodes and the material placed in between (Fig. 3b). Copper electrodes, placed equidistantly along the edges with a penetration depth of 3 mm and a width of 5 mm, are mounted on the fixture. A total of 16 electrodes in addition to a grounding electrode were used to conform to the Sigma Tome II system.

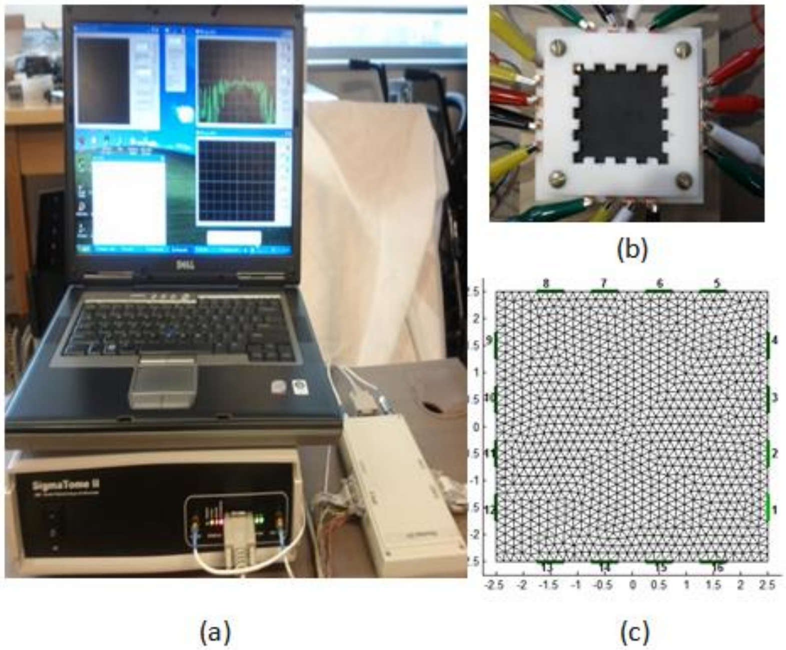


Fig. 3. (a) EIT sensor setup with Sigma Tome II and scan-head, (b) fixture with PSCR sample (c) FEM model with CEM generated using Distmesh

3. 3. Physical Model

The physical modeling of the PSCR is conducted in EIDORS by constructing a 2-D Finite Element Mesh with the same dimensions as the physical sample as shown in Fig. 3:c. This is part of the forward model which is used to solve the inverse problem resulting in image reconstruction. 1066 nodes and 2066 triangular elements constituted the Finite Element model (FEM) where sixteen rectangular shaped electrodes were selected. A Complete Electrode Model (CEM) was chosen as opposed to a point electrode model in order to enhance image reconstruction. This allowed us to define the electrode shape, size and impedance. Four equidistant nodes were placed at each of the rectangular shaped electrode contact locations. The electrode contact impedance was set equal to 0.01 ohms. Furthermore, a uniform mesh density function was chosen for the mesh edge length.

3. 4. EIT Inverse Problem

A non-iterative difference imaging solver is the only means of EIT evaluation being considered. According to (Graham and Adler,2006),difference imaging improves the 2D approximation of the 3D electrical field changes and avoids issues regarding unknown electrode contact impedance and errors due to electrode position misplacement. The domain under investigation is initially discretized using a FEM. A solver based on the least squared method is used for difference imaging; where $\hat{c}$ is the proportional change in conductivity, v is a given set of voltage measurements and the Jacobian matrix $\mathcal{T}$ as seen in Eq. (3). Where $\mathcal{T}$ is a function of the FEM, the background conductivity as well as the current injection. However, the addition of noise to a given set of voltage measurements v will greatly amplify errors in image reconstruction if the Moore-Penrose pseudoinverse is directly used. A regularized term R is essential for solving the ill conditioned inverse problem. It is anticipated that the change of conductivity between the elements of the reconstructed image exhibit smooth changes in conductivity. Therefore, the laplacian image prior as described by (Adler and Lionheart, 2006) is chosen for R hence resulting in images that allow for smooth transitions between elements. Weighting the regularization term is achieved by selecting a scalar hyper-parameter λ. The L-curve was used in order to estimate a suitable hyper-parameter for our application. The reader is referred to (Graham and Adler, 2006) for a description of alternative objective evaluation schemes for hyper-parameter selection. In addition, (Holder, 2005) provides a more detailed theoretical background and investigation of EIT and alternative approaches for solving the inverse problem.

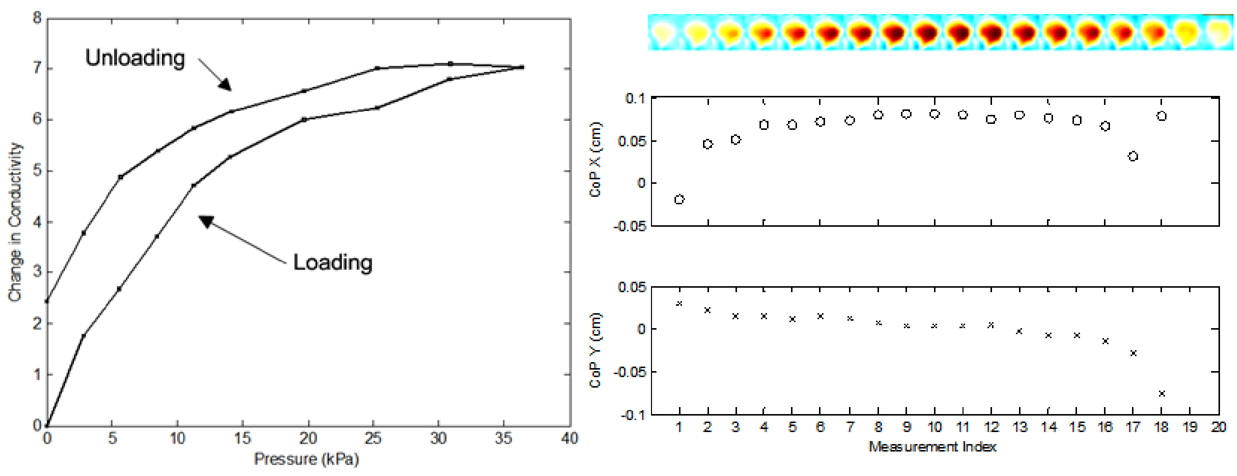
$$\hat{c} = (\mathcal{J}^T\mathcal{J} + \lambda R)^{-1}\mathcal{J}^T v \quad (3)$$

4. Sensor Characterization and Discussion

Two experiments are discussed which investigate the pressure response and image quality of the EIT sensor. Pressure readings used for calibration were calculated based on the mass measurements from precision weight scale (AND EJ-4100) placed underneath the sensor fixture.

4. 1. Variable loading Experiment

A 4 cm^2 square shaped copper sheet was placed at the centre of the PSCR sample where pressure was applied. Copper was used in this case but it can be easily substituted with any conductive fabric with lower volume resistance relative to the PSCR. Fixed weights were added to the copper contact and the pressure was incremented up to the maximum applicable range of 35 kPa then decremented to the no load state. The trials were conducted three times to ensure repeatability. The calibration curve is shown in Fig. 4:a. There is an evident non-linear relationship between pressure and the change in conductivity relative to the no load state of the sensor. The hysteresis is calculated to be 34.5 % of the rated output span .The CoP deviation in the X and Y axis from the centre of the phantom are shown separately in Fig. 4:b, for each normal load measurement. Since the contact is not secured on the PSCR sheet, larger deviations in the CoP are realized at pressures less than 5 kPa. This could be attributed to the fact that the copper sheet is touching the surface of the PSCR without any preloading to ensure minimal contact.



(a) (b)

Fig. 4. (a)Sensor calibration and hysteresis curve (b) Top, Sensor image for variable loading with fixated contact location at the centre and a stimulated area of 2 cm^2. From left to right, pressure is increased to 35 kPa and then decremented back to a no load state (b) Bottom, the variations of the CoP in the X and Y directions for constant location at the centre of the phantom and under variable normal load

4. 2. Pressure Map Validation

In order to investigate the consistency of the images over the entire sensing area, the location of a square copper contact, with a surface area of 4 cm^2 was varied under a fixed load of 1kg. Fig. 5 shows how the change in location of the stimulated area is detected over half the sensing area due to the symmetric nature of the design. The developed EIT pressure sensor based on the CS57-7RSC PSCR was able to detect the pressure profile over the complete sensing area. According to Fig. 6, a total of 25 positions following the same sequence and covering the entire sensor, surface show that the images had the poorest resolution at the centre of the phantom. The resolution improved as the distance to the electrodes was reduced. Moreover, shape deformations were found to be more significant with increased proximity to the boundary electrodes. The largest CoP position errors were also recorded when the stimulated area was at the centre as shown in positions 10 to 15 in Fig. 5. Performance enhancement can be achieved by increasing the number electrodes at the boundary. Alternative methods of electrode attachment on the conductive polymer as well as shape, size and position selection of the electrodes are all contributing factors to the effectiveness of the sensor.

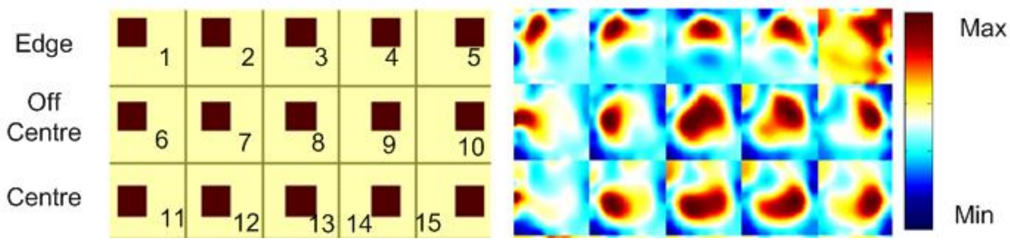


Fig. 5. Position 1 to 15: from left to right, top to bottom. Applied pressure at the specified location depicted on the left and the actual corresponding sensor image to the right. Images are for 1kg load with 10 second interval between successive profiles. Red regions depict positive changes in conductivity

The hysteresis effect is visualized in the images found in Fig. 5 where previous stimulated areas remain present in consecutive measurements with lower amplitude. This caused the images to be blurred and causes misinterpretation of the actual current pressure profile, making it harder for the stimulated area to be detected. However, the use of a pre-specified ROI reduced the unwanted effect of PSCR hysteresis and artefacts when acquiring the pressure value from the image.

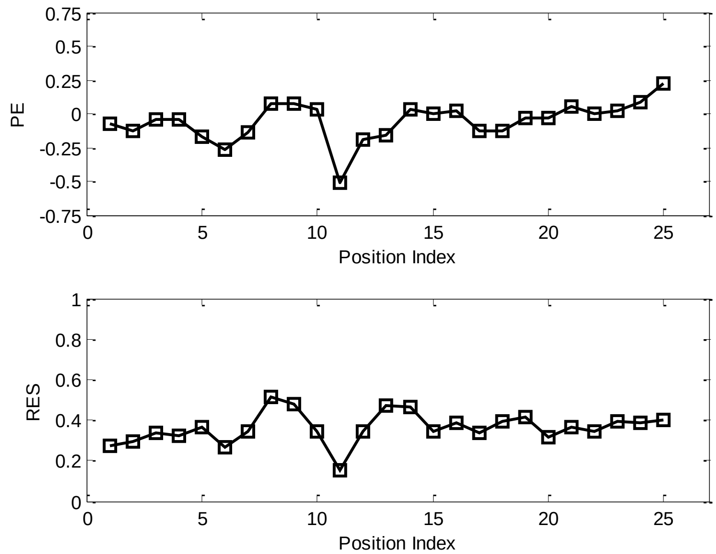


Fig. 6. Position Error and Resolution for the 25 positions where the target CoP is varied from (-1, 1) to (1,1) in 0.5 cm increments in the x-axis followed by the y-axis

5. Conclusion

An EIT based pressure sensor using CS57-7RSC was designed and characterized in this paper for use as a robotic artificial skin interface. The sensor design and the physical modelling were presented. Furthermore, the EIT setup and configuration used for data acquisition and image reconstruction was introduced in detail. The sensor exhibited a nonlinear relationship between pressure and relative change in conductivity. The PSCR material was characterised with an applicable pressure range of up to 35 kPa and a hysteresis of 34.5 % of the rated output span. Pressure profile images tracking a pressure stimulus over the entire sensing range were demonstrated using experimental data. In addition, the resolution and position error were found to be dependent on the location of the stimulus relative to the boundary electrodes.

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