Wearable PZT sensors for distributed soft contact sensing

(Design and Signal Conditioning Manual)

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Introduction

For any soft wearable device the information about the surrounding environment and interactions is an important performance aspect. A sensor design becomes challenging when the target component has a non-uniform, agile, high resolution, and soft surface. Recent developments in wearable sensor technology have made it possible to embed piezoelectric element (PZT) based sensors, conductive fabrics, electro-active polymers and other families of stretchable and flexible sensors into soft silicone.

We have developed PZT based sensors for wearable applications owing to their low cost, high sensitivity, high customization and low hysteresis properties. Multiple PZT sensors can be distributed over the actuation surface to provide multiple points for sensing. Piezoelectric ceramics are known to be highly sensitive to normal forces applied and can be embedded into silicone substrates [1]. Our sensors can have multiple pixels of PZT elements discretely distributed over a surface area in the form of grid. The PZT sensing elements are connected using flexible circuit tracks manufactured by laser cutting the copper-plated kapton (polyamide) material. The construction is then embedded inside silicone material for additional support and electrical insulation.

The novelty in our design includes customizability, high density, parallel information gathering and the possibility of active feedback control using sensed information [2]. The presented prototype's mechanical and functional capacities are promising for applications in biomedical systems where soft, wearable and high precision sensors are needed these sensors and their applications are highly desired in human-robot interaction, biomedical robotics and biomimetic robotics in order to provide effective sensory feedback. The sensor applications can also be extended further wherever the similar performance is necessary.

System Overview

1. Sensor Design :

Sensor fabrication begins with selection of pixel-dimensions and density required for the specific application. We selected 2 x 2mm^2 size PZT element for the prototype sensor design [2]. This PZT element is then sandwiched between two copper-kapton electrodes for connections. Sensors can be of different sizes and can be oriented in the form of matrix over a distributed area. Figure 2 shows a 8x2 matrix distribution and a 3 sensor circular perimeter distribution of PZT sensors for two different applications. Also, the novel manufacturing procedure enables placement of two electrodes on top of each other which helps to reduce the area required for electronic tracks and further improves the sensor density for distributed sensing.

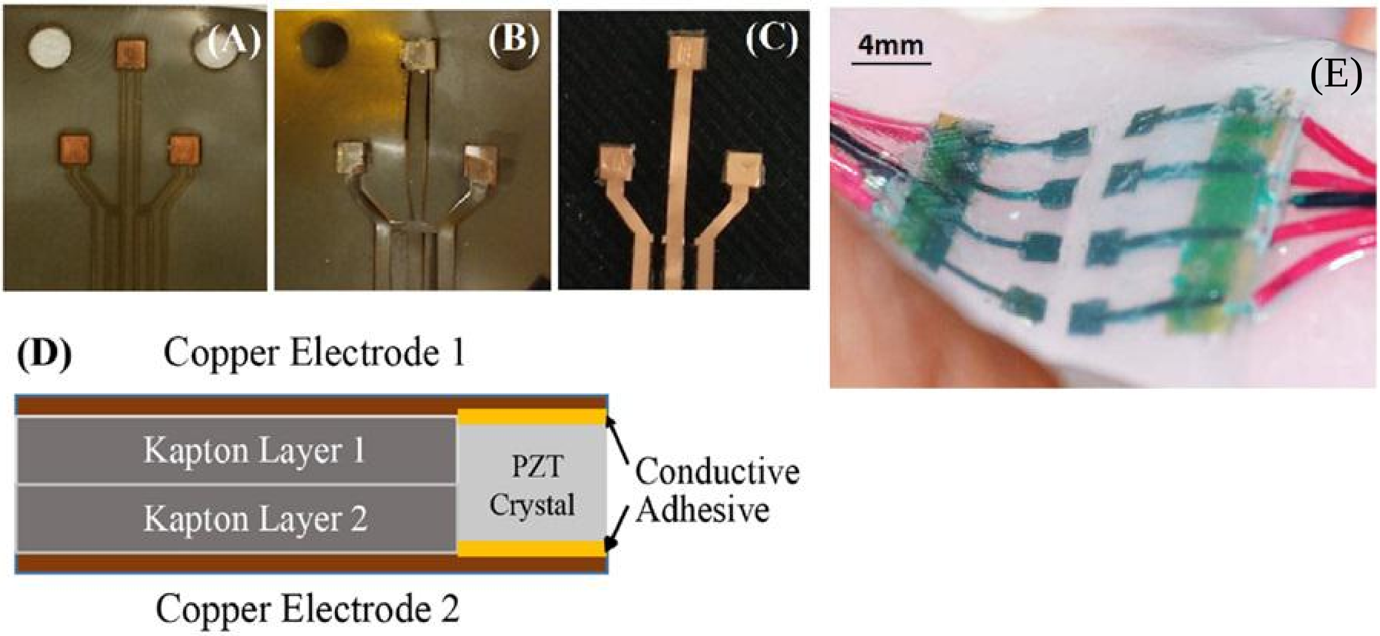

Figure 1. Sensor manufacturing process of the PZT sensor prototype with 2 x 2mm^2 PZT elements with laser engraving(A), adhesive application(B), sensor placement(C), and sensor schematic (D). Silicone integrated 8x2 PZT sensor matrix demonstrating flexibility and distribution capabilities (E).

2. Electronics and Signal Conditioning:

PZT material converts applied mechanical stress (σ) into proportional electrical charge (q). The Charge generated is very small and susceptible to external electrical loading. Therefore, a high input impedance charge amplifier is used to amplify the sensor signal and convert it into voltage proportional to the applied stress. The electrical equivalent circuit for PZT sensor is as shown in Figure 3A where charge(q=k σ) generated by mechanical stress across the piezo capacitor give rise to excitation voltage. This excitation voltage(V) is amplified and low pass filtered using the charge amplifier. For our sensor the sensitivity is around 0.25V/N [2]. The transfer function for piezo circuit can be easily deducted as:

$$\frac{Vout\ (s)}{\sigma(s)} = \frac{k\tau s}{(1 + \tau S)} \qquad (1)$$

Where, $\tau = RpCp$.

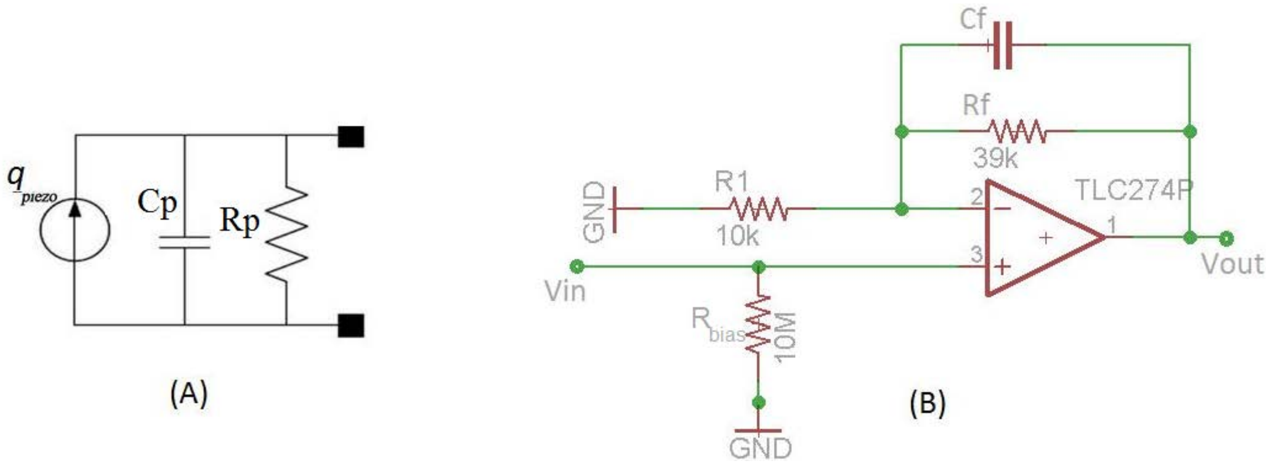

Figure 2 : Electrical equivalent circuit of PZT sensor (A) and Charge amplifier using OpAmp (B)

Also, the transfer function for charge amplifier is given as:

$$\frac{Vout\ (s)}{Vin(s)} = \frac{Rf}{R1(1+RfCfs)} + 1 = \frac{G}{(1+\ \tau 2s)} + 1 \qquad (2)$$

Where, *G*= DC gain and $\tau 2 = RfCf$.

Now, from equations (1) and (2) overall transfer function of PZT sensor can be written as:

$$\frac{Vout(S)}{\sigma(s)} = \frac{Ks}{((1+\tau s))}\left(\frac{G}{(1+\tau 2s)} + 1\right) \qquad (3)$$

3. Reading Data:

As seen from Equation (3) the overall transfer function for PZT sensor with amplification stage acts as an active band-pass filter with tunable gain G and time constants τ and τ_2.

For example, we practically obtained C_p=1F, k=0.25 V/N, R_p>>R_{bias}=10MΩ. Now, with R_1= 10k , R_f=39k and C_f= 47ηF, The overall transfer function performs like a band pass filter with lower cutoff frequency of **15 Hz**, upper cutoff frequency of **86Hz** and overall dc gain of **1.2**. These values can be tuned depending upon the application requirement.

However, it is important to note that once sensor is integrated inside soft silicone the transfer function is also modulated by the thickness of the silicone layer discussed in detail in [1].

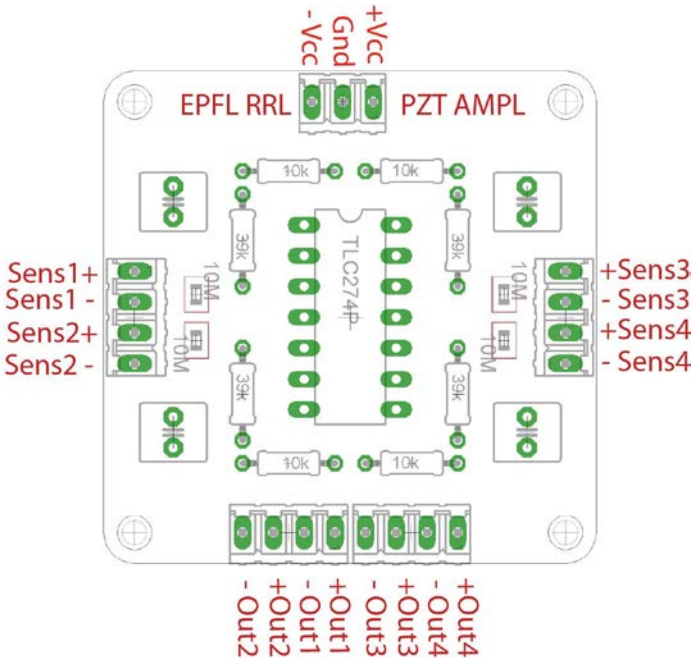

Figure 3: Printed Circuit Board Schematic for PZT sensor interfacing

The charge amplifier circuit is implemented using TLV2774 [3], a high slew rate quad OpAmp IC, as shown in Figure 3. This circuit is driven using dual power supply ranging from 2.5V - 5.5V. A single PCB can simultaneously interface 4 PZT sensors as depicted in Figure 4. Where, **Sense+/-** is sensor input and **Out+/-** is corresponding amplifier output.

Signal generated by PZT sensor is low pass filtered to remove high frequency noise. We recorded sample response for the PZT sensor in two cases as shown in Figure 4.

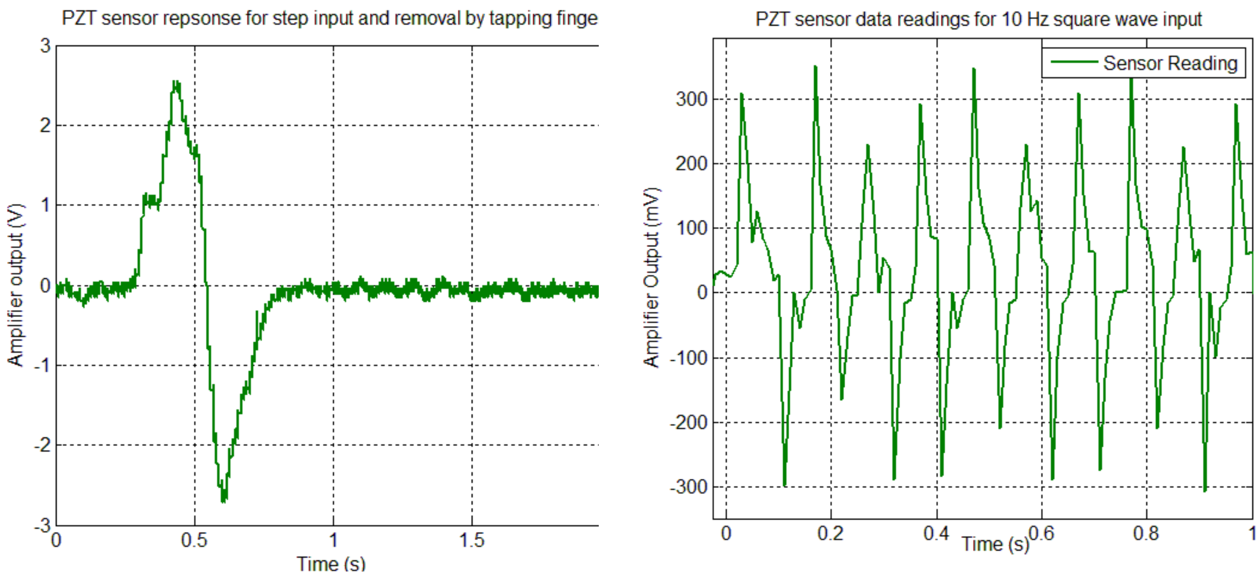

Figure 4: PZT sensor response as recorded using charge amplifier circuit for finger tapping and removal (A) and continuous step input using SPA-skin [2] at 10 Hz (B)

References :

[1] Acer, Merve, et al. "Development and characterization of silicone embedded distributed piezoelectric sensors for contact detection." Smart Materials and Structures 24.7 (2015) : 075030.

[2] Sonar, Harshal Arun, and Jamie Paik. "Soft pneumatic actuator skin with piezoelectric sensors for vibrotactile feedback." Frontiers in Robotics and AI 2 (2015) : 38.

[3] Datasheet TLV2774 Online: http://www.ti.com/lit/gpn/tlv2774