Improving Accuracy in E-Textiles as a Platform for Pervasive Sensing

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***Abstract*—Recently Electronic Textile (E-Textile) technology enables the weaving computation and communication components into the clothes that we wear and objects that we interact with every day. E-Textile enables the design and development of a broad range of pervasive sensing systems such as smart bed sheets for sleep posture monitoring, insoles in medical shoes for monitoring plantar pressure distribution, smart garments and sensing gloves. However the low cost of E-Textiles come at the cost of accuracy. In this work we propose an actuator-based method that increases the accuracy of E-Textiles by means of enabling real-time calibration. Our proposed system increases system accuracy by 38.55% on average (maximum 58.4%).**

I. INTRODUCTION

Recent technology has enabled the weaving of computation and communication components into the clothes that we wear and objects that we interact with every day. This is enabled by a technology called E-Textiles. E-Textile is an inexpensive composite yarn made of fibers coated with conductive polymer. Due to the characteristics of E-Textiles such as flexibility, low cost and portability, E-Textile-based wearable design has become increasingly promising in a wide area of important pervasive sensing systems such as carry-on healthcare devices. Examples of these systems include smart bed sheets used for sleep posture monitoring [1], insoles in medical shoes for monitoring plantar pressure distribution [2] and smart sheets used on surfaces such as chairs and tables [3]. They also enable creating smart garments [4], [5] used in a variety of monitoring application such as monitoring arterial blood pressure, and in sensing gloves [6] that are able to detect posture of the hand used in applications such as assessment of ergonomics. Current research has focused on applications and building frameworks for E-Textile systems [7], [8], [9]. The popularity of E-Textiles is mainly due to their low-cost and non-metallic characteristics which make them a good candidate for medical applications. However the low cost of E-Textiles come at the cost of accuracy.

Providing a balance trade-off between cost and accuracy of medical systems used for monitoring is very important. E-Textile based platforms that enable the instrumentation of low cost devices for medical monitoring sometimes lack the accuracy required by the medical applications that they target. In-order to make E-Textiles a suitable platform for pervasive monitoring applications new methods need to be developed to account for these inaccuracies in different levels of design. In this work we propose an actuator-based method that increases the accuracy of E-Textiles by means of enabling real-time calibration.

E-Textile sensors suffer from different sources of error. One of these sources is sensor uncertainty which is due to manufacturing and sensor degradation in time. The ADC resolution limitation is another kind of inherent systematic error. For example, the quantization error of an 8-bit ADC is 0.39%. In addition to the mentioned errors the most problematic property of E-textiles is the time drift property. Due to the characteristics of E-Textiles the polymer in the material undergoes mechanical strain when pressure is asserted. This mechanical strain affects the contact between the polymer and the electrodes and causes a property called time drift. The time drift property causes the value read from the sensor to change as a function of time. This property is the main source of uncertainty in E-Textile based systems undergoing different pressures at different times.

There has been recent research attempts targeting the accuracy of E-Textiles [3] and designing efficient sensor structures and sampling techniques for E-Textile-based systems [10].

E-Textile sensing systems gather sensing information from the applications they target. On the other hand, haptic feedback by means of actuation provides a way for transferring information back to the application. Haptic feedback has been recently used in wearable applications by using tactile stimulation as an alternative to the traditional methods of auditory or visual feedback. It has been used in a broad range of applications from biomedical and tele-surgery to robotics and virtual reality [11], [12]. In order to convey rich information, multi-source actuators are used in large numbers based on application requirements. An example is in [13] where 400 tactile stimulators are used in a tactile television system for the blind. Since wireless sensor networks and body area networks are gaining momentum in enabling technologies in healthcare, the integration of actuation capabilities in sensor nodes has proven to enable many interesting possibilities.

With the integration of actuation with sensing capabilities in sensor nodes, many new applications have appeared [14], [15]. The most similar to our work is previous work in combining actuators and sensors in the context of self-testing [16], [17]. In these methods a built-in actuator is used to verify the functionality of a pressure sensor and therefore improves the reliability of a pressure measurement.

To our knowledge this is the first attempt at enabling a more accurate sensing platform for E-Textiles by means of actuation. The main goals of this paper is twofold: (1) to model the inaccuracies in E-Textiles, and (2) to propose a new online calibration method that uses actuations to produce forces and uses the system response to these known forces to build an on-line output response of the system.

Our proposed method uses light-weight actuators with

978-1-4799-0330-6/13/$31.00 ©2013 IEEE

characteristics similar to vibrators used in cell phones and pager motors. The proposed sensing platforms comprises actuators embedded in the E-Textile sensor. The actuators produce known forces at specific intervals and the system measures the E-Textile response to these forces. The measured values are then used to calibrate the accuracy of the system.

The rest of the paper is organized as follows: In Section II we provide preliminary information on the basic components of our proposed sensing platform. E-Textile pressure sensor structure and vibro-tactile actuators are described as the basic components of our platform. In addition, information on the system architecture of our platform is also described in this section. Characteristics such as time drift and repeatability which are the main reasons for inaccuracies observed in E-Textile systems are measured and modeled in Section III. In Section IV, we describe our stimulation platform and how we can produce different forces by means of actuation. The stimulation platform is used to develop an on-line method for extracting E-Textile response curve, described in Section V. We present our experimental results in Section VI and draw conclusions in Section VII.

II. PRELIMINARIES

In this section we present preliminary information on E-Textile sensors and actuators, and describe the system architecture of our proposed sensing platform.

A. *E-Textiles*

E-Textile is a composite yarn made of fibers coated with conductive polymer. The natural structure of E-textiles is loose and inside fibers are air gapped. The initial throughout resistor between the top-bottom surfaces is low. When extra pressure is asserted on the surface, the intra fibers are squeezed together and the throughout resistor becomes smaller. Here, the resistor is inversely proportional to the pressure imposed.

An E-Textile based sensor has a three-stacked layer structure. The sensing material is sandwiched within two conductive pads. The conductive layer can be conductive fabrics, copper foil tape or conductive threads based on application design choices. In this work, in order to maintain the flexibility of the sensor and the textile feel we use conductive thread and conductive paper for the conductive layer. Figure 1, shows two examples of E-Textile sensors made using different conductive material. In this sensor, E-Textile acts like a pressure sensitive resistor. When force is applied, the resistance of the three-stacked E-Textile sensor decreases.

Fig. 1. E-Textile Sensor Structure

B. *Actuators*

There are two main approaches for tactile stimulation: (1) electro-tactile (2) and vibro-tactile [18]. Electro-tactile stimulation uses electrodes to produce sensation through electric current. By changing electrode size and the properties of the applied waveform, different stimulations can be produced. On the other hand, vibro-tactile stimulation uses mechanical vibrations. It provides fewer control parameters for stimulations but its cost, size and robustness make it a more popular choice in various applications.

In this work we provide tactile stimulation through vibro-tactile actuators with characteristic similar to vibrators used in cell phones (and pager motors). These actuators are good candidates since they are lightweight, inexpensive and small. However this actuator comprises a motor with an eccentric mass. Applying voltage to the motor, results in rotation of the motor, which in turn results in stimulation. Higher voltages result in higher motor rotation velocities which are felt as higher intensity stimulation.

C. *System Architecture*

Figure 2 shows the framework of our proposed system. The system comprises a client and a host part. In the client or the end device, the E-Textile pressure sensor array (shown in Figure 3) is scanned with the use of multiplexors. The sensing data is then acquired by the microcontroller, it is packaged and transferred to the host receiver side through wireless RF circuit. The microcontroller we chose in our experiments is the MSP430f2274. The A/D converter's resolution is 10 bits, and the sample rate is 100kps. CC2500 is used for the wireless chip. The communication protocol used to transfer the data is SimpliciTI. SimpliciTI network protocol is a proprietary low-power radio frequency protocol targeting simple, small RF networks. This network protocol can be considered a complement to ZigBee (suitable for larger networks). In the current implementation we have one client and a single host.

The number of end devices in the SimpliciTI network protocol can be extended to 100 and each of the sensing surfaces can become much larger, by simply adding multiplexers in front of the ADC converters. In the host or the access point, the sensed data is processed by a PC when received by the RF chip. A UART to USB convertor (based on MP2010) is designed for interface compatibility.

III. MODELING CHARACTERISTICS AND ACCURACY IN E-TEXTILES

In this section we provide information on different characteristic of E-Textiles and their response to pressure. Characteristics such as time drift and repeatability which are the main reasons for inaccuracies observed in E-Textile-based systems are measured and modeled.

A. *Pressure-Resistance Curve*

Pressure to resistance transduction characteristics were obtained by applying known weights on a single sensor. The sensor under-test was a 1cm*1cm sensor made in the three-layer stacked structure described in Section II-A. A vibrator of weight 1.2g was glued onto the sensor. Measurements indicate

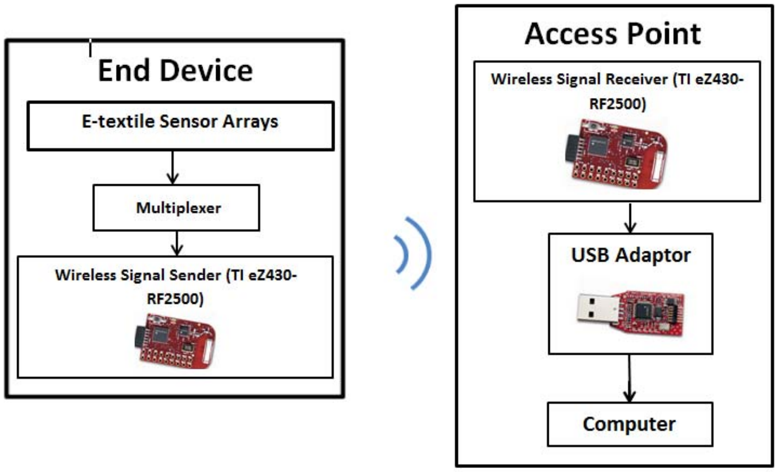

Fig. 2. System Architecture

Fig. 3. E-Textile Pressure Sensor Array

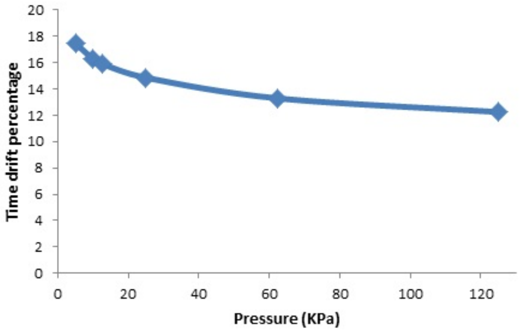

Fig. 4. Pressure-Resistance Curve

that the effect of the weight of this actuator is negligible in our experiments (using a 1cm diameter of the actuator, a 1g weight generates around 125Pa pressure to the sensor).

In order to obtain the pressure-resistance curve, 20g, 40g, 80g, 100g, 200g, 500g 1000g weights were used. Averaged results of five sets of tests on five different single sensors are shown in Figure 4.

It can be observed from Figure 4 that the first part of the curve has a deep drop in resistance which is approximately linear and after around 10kPa the curve shows a shape which can be represented using rational fit. Pressure values larger than 150kPa were also applied but no obvious further resistance drop was observed. Measurements indicate that in the final saturation condition the asymptotic resistance value is around 4 $k\Omega$. Equation 1 describes the pressure to resistance transduction characteristics of the E-Textile sensor we used:

$$R = \begin{cases} 102 - 8 \times p & for\ p < 10 \\ \frac{0.1167 \times p + 948.7}{p + 23.17} & for\ 10 \leqslant p \leqslant 150 \\ 4 & for\ p > 150 \end{cases} \tag{1}$$

B. *Time Drift*

As described earlier the resistive polymer is the key material for pressure to resistance transduction. When pressure is applied to the surface of this layer, a mechanical strain is inevitable. This strain affects the contact between the polymer layer and the conductive layers which act as electrodes and thus time drift is introduced in measured resistance.

Experiments were carried out to find the pattern of the sensor behavior for short term time drifts. Constant pressure values of 5, 10, 12.5, 25, 62.5 and 125 kPa were applied to the surface of the sensor while the sampling frequency for resistance reading was set at 100Hz. In our experiments we considered a resistance value as *stable* if the same sample value was measured in 20 consecutive samples or more. The sampling time interval of 5 minutes was used and the initial resistance value was recorded at the first stable value. The results obtained for the time-drift experiment are shown in Figure 5.

It can be seen from Figure 5 that for all pressure values applied, an obvious time drift effect is observed, which is over 10% within a short interval of sampling. Figure 5 also reveals that as the applied pressure increases, the short term time drift effect decreases logarithmically. Similar effects have been shown in the experiments conducted by Z. Del Prete et al [19]. [19] also concludes that the time drift effect can be considered negligible after longer sampling intervals, (specifically 4 hours in conducted experiments).

C. *Repeatability*

Intuitively, it is assumed that all sensors constructed in the same structure and dimension as mentioned above could

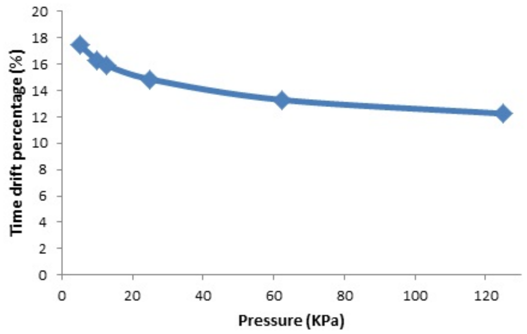

Fig. 5. Time Drift Effect for Different Applied Pressures Values

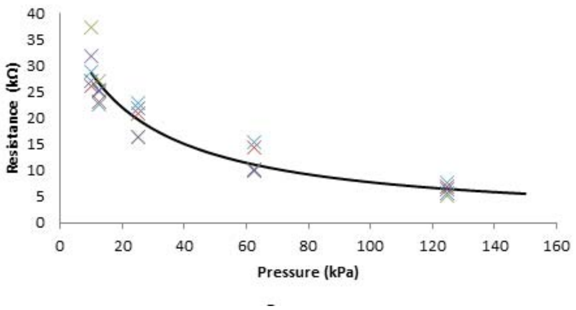

Fig. 6. Repeatability among Different Sensors

all be characterized using Equation 1. In order to check the deviations from the equation, measurements were carried out using various individual sensors which were each built in the same structure and dimensions. The results obtained are shown in Figure 6 for five different sensors.

It can be observed from Figure 6 when low pressures were applied to the sensor, namely less than 10 kPa, the measured deviations are relatively large, around 20%. The variances between individual sensor resistances are large as well. As the pressure values increase, the curve predicts the resistance value fairly accurate, with the deviation being only around 5%.

IV. PRODUCING FORCE BY MEANS OF ACTUATION

Integrating actuation capabilities in a sensor node can provide a method for applying controlled forces to the desired sensing location. Figure 7 shows this structure where in addition to the E-Textile pressure sensor, a vibro-tactile actuator which can be activated independently, is used. With this structure, a controlled force can be applied on the surface of the E-Textile pressure sensor. This controlled force can then be used to apply a known stimulus and measure the changes in the sensor output resistance. The sensor output resistance as a response to a known actuation can provide information which is valuable in increasing the accuracy of the readings. In this section, we describe parameter selection for the stimulation pulse to achieve a desired force.

As mentioned in Section II-B, one of the limitations of vibro-tactile actuators which are used in this paper is imposing only one control variable: voltage supplied to the motor. Higher voltages result in higher motor rotation velocities which result in higher intensity stimulation. In this work, we produce stimulation through on-off pulses in a square-wave shape. By changing the duty cycle of these pulses we add another control variable to the system. In detail, stimulation is produced through trains of rectangular pulses. The main characteristics of the excitatory waveform are: applied voltage, pulse frequency and duty cycle. Note that this frequency is different from the frequency which produces the vibrations in the motor. This is the frequency of the rectangular pulses in the excitatory waveform.

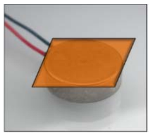

Fig. 7. A Single Sensor-Actuator

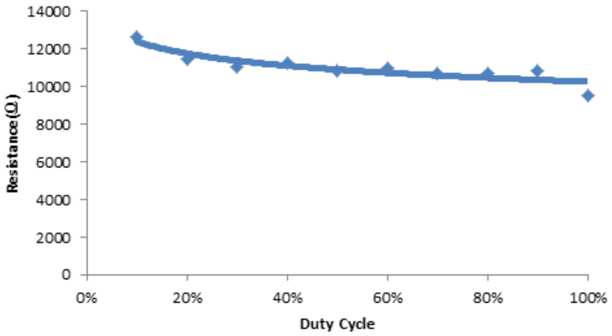

Fig. 8. Resistance Output vs. Control Signal Duty Cycle

An actuator laid on top of the E-Textile sensor as shown in Figure 7 can be considered as a variable weight. As described, the main control variable we use to change the stimulation of vibro-tactile actuations is the duty cycle of trains of rectangular forces. By changing the duty cycle of these pulses we control the stimulation applied on the E-Textile surface and in turn the output resistance. The sensor output resistance as a response to a known actuation can provide valuable information which can be used in increasing the accuracy of resistance readings. Section V describes how we use this information to increase the system accuracy. Figure 8 shows the resistance output of an E-Textile sensor with different duty cycles for the stimulation of rectangular pulses.

Please note that the resistance value shown in Figure 8 corresponds to the mean resistance during the actuation period at each duty cycle.

V. ONLINE ACTUATION-BASED CALIBRATION

Our proposed approach for improving the accuracy of E-Textiles as a sensing platform is based on combining actuators into sensing points. By applying known forces to the E-Textile sensor and measuring the senor's output resistance as a response to this known input stimulus, we build a model of sensors output function. Figure 9 shows the resistance output of a single element E-Textile sensor in different states of the system. The results are gathered through measurements at different times when the system has undergone different forces in its measurement history.

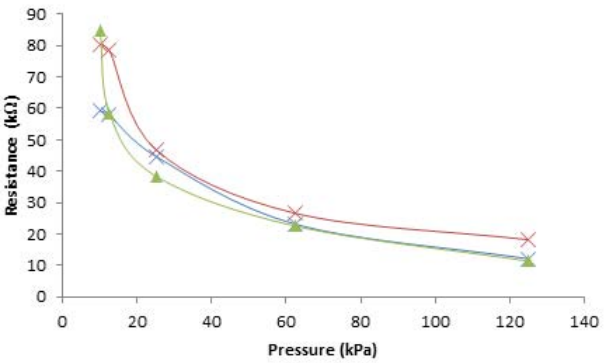

Fig. 9. Resistance vs. Pressure at Different System Status.

As Figure 9 shows the history of the system has a strong effect on the resistance response of the system. Our proposed approach uses the knowledge of resistance responses to different actuation stimulations to understand the current status of the system. Once the online pressure-resistance curve is derived, the curve is used to find pressure values based on measured resistances. The calibration process is an online one as it happens not only at the beginning but throughout the sensors system lifetime.

Algorithm 1 Online Actuation-Based Calibration

```
1: OnlineCalibration()
2: currentModel = initialModel;
3: actuationInterval = interval;
4: While (system alive)
5: wait actuationInterval;
6: updatedModel = UpdateModel()
7: if ($\sum_f (currentModel(f) - updatedModel(f)) >= \alpha$)
   // f: related to duty cycle 20%, 50%, 100% then
8:     actuationInterval /= 2;
9: else
10:    actuationInterval += beta
11: end if
12: currentModel = updatedModel;
13: EndWhile
```

Algorithm 2 Update model

```
1: UpdateModel()
2: For duty cycles $d$ = 20%, 50% and 100%
3:     Apply duty cycle $d$ to actuators to apply a known force
       f(d) on textile;
4:     r(f(d)) = Measure the resistance for the applied force;
5: End For
6: Model = Fit a curve using (r(i), f(i)); // i = 1..3
7: return Model;
```

Algorithm 1 describes our proposed approach for performing online calibrations using actuation. Actuation phases happen at intervals which is experimentally determined (line 2). At each time interval the pressure-resistance curve of the system which is used for translating resistance readings to pressure values is updated by applying known forces by means of actuation. The system starts with an initial model which is different for each sensor based on manufacturing and other issues discussed earlier. A procedure called UpdateModel (line 6) is in charge of updating the pressure-resistance model at each actuation interval (see Algorithm 2). The actuation interval is then adjusted based on the difference of the current model of the system and the updated derived model (line 7-10). If this difference is higher than a certain bound (α) then the interval between actuation phases where models are updated is cut in half (line 8). On the other hand if the difference between models is insignificant the actuationInterval is increased linearly (line 10).

Algorithm 2 is in charge of deriving the updated model at each actuation interval, and works as follows: three different forces are applied using three different duty cycles in actuation (line 2-3). In our experiments we use 20%, 50% and 100% duty cycles. The number of actuation points can be configured to be larger than three to allow a more accurate model creation. The resistance at each actuation point is recorded (line 4) and is used to build a model based on Equation 1 (line 6). Please note that we allow a specific time between each actuation in order to allow the system to return to its resting status and eliminate the time-drift problem in our modeling. This time interval is determined based on the applied pressure since as discussed in Section III-B the time-drift interval varies in different pressure levels.

VI. EXPERIMENTAL RESULTS

In order to validate our proposed approach and test the efficiency of our system we demonstrated the following experiment: we used a single sensor and actuator and placed the sensor system in an unknown status by applying different forces and weights to the system. We then applied our online calibration method (Algorithm 1) to find an updated model for the system. After the calibration phase, in order to test the validity and accuracy of our approach, we applied four different pressure values and used the updated model to infer measurements. The original and the updated model are depicted in Figures 10 and 11.

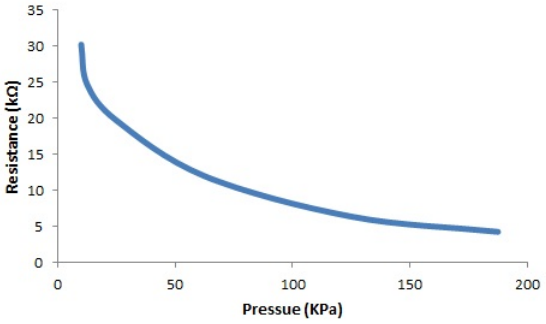

Fig. 10. Initial Model

Normally if the calibration phase is not applied, the initial model (Figure 10) is used to translate resistance values read by the micro-controller to their equivalent pressure values. However, the problem which motivated this work, was that the E-Textile pressure sensor undergoes changes through time which injects uncertainty in the model. Therefore, using the initial model to translate resistance values to pressure values

TABLE I. ACCURACY IMPROVEMENTS

True Pressure (KPa)	**Pressure using Initial Model (KPa)**	**Pressure using Updated Model (KPa)**	**Initial Model Error (%)**	**Updated Model Error (%)**	**Error Improvement (%)**
50	57.44	54.35	14.9	8.7	58.4
60	67.88	65.08	13.1	8.5	55.3
70	73.46	72.94	4.9	4.2	11.7
80	75.88	78.76	5.2	1.5	28.8

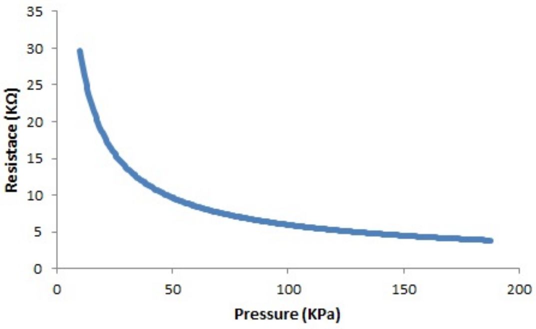

Fig. 11. Updated Model

would suffer from various errors. The updated model (Figure 11) derived from Algorithm 1 represents a more recent model of the system. Table I shows translated pressure values obtained from both models when known pressure values are applied.

As results of Table I show, our proposed approach results on average 38.55% (maximum 58.4%) accuracy improvements over using the initial model without undergoing the calibration phase.

VII. CONCLUSIONS

Electronic Textile (E-Textile) technology enables low-cost design and development of a broad range of pervasive sensing systems, by weaving computation and communication components into the clothes that we wear and objects that we interact with every day. But the low cost of E-Textiles comes with their low/variable accuracy. In this work we proposed an actuator-based method that increases the accuracy of E-Textiles by means of enabling real-time calibration. Our method uses intervals of actuations to build real-time models of system response which is then used to infer resistance measurements. Our approach increases the measurement accuracy by 38.55% on average and a maximum accuracy of 58.4%.

REFERENCES

[1] S. Devot, A. Bianchi, E. Naujokat, M. Mendez, A. Brauers, and S. Cerutti, “Sleep monitoring through a textile recording system,” in *Engineering in Medicine and Biology Society, 2007. 29th Annual International Conference of the IEEE*. IEEE, 2007, pp. 2560–2563.

[2] L. Shu, T. Hua, Y. Wang, Q. Li, D. Feng, and X. Tao, “In-shoe plantar pressure measurement and analysis system based on fabric pressure sensing array,” *Information Technology in Biomedicine, IEEE Transactions on*, vol. 14, no. 3, pp. 767–775, 2010.

[3] M. Rofouei, W. Xu, and M. Sarrafzadeh, “Computing with uncertainty in a smart textile surface for object recognition,” in *Multisensor Fusion and Integration for Intelligent Systems (MFI), 2010 IEEE Conference on*. IEEE, 2010, pp. 174–179.

[4] M. Pacelli, G. Loriga, N. Taccini, and R. Paradiso, “Sensing fabrics for monitoring physiological and biomechanical variables: E-textile solutions,” in *Medical Devices and Biosensors, 2006. 3rd IEEE/EMBS International Summer School on*, sept. 2006, pp. 1 –4.

[5] Y. ting Zhang, C. Poon, C. hung Chan, M. Tsang, and K. fai Wu, “A health-shirt using e-textile materials for the continuous and cuffless monitoring of arterial blood pressure,” in *Medical Devices and Biosensors, 2006. 3rd IEEE/EMBS International Summer School on*, sept. 2006, pp. 86 –89.

[6] J. Edmison, M. Jones, Z. Nakad, and T. Martin, “Using piezoelectric materials for wearable electronic textiles,” in *Wearable Computers, 2002.(ISWC 2002). Proceedings. Sixth International Symposium on*. IEEE, 2002, pp. 41–48.

[7] D. Marculescu, R. Marculescu, and P. K. Khosla, “Challenges and opportunities in electronic textiles modeling and optimization,” in *Proceedings of the 39th annual Design Automation Conference*. ACM, 2002, pp. 175–180.

[8] S. Park, K. Mackenzie, and S. Jayaraman, “The wearable motherboard: A framework for personalized mobile information processing (pmip),” in *Proceedings of the 39th annual Design Automation Conference*. ACM, 2002, pp. 170–174.

[9] M. Chandra, M. T. Jones, and T. L. Martin, “E-textiles for autonomous location awareness,” *Mobile Computing, IEEE Transactions on*, vol. 6, no. 4, pp. 367–380, 2007.

[10] M. Rofouei, M. Potkonjak, and M. Sarrafzadeh, “Energy efficient e-textile based portable keyboard,” in *Low Power Electronics and Design (ISLPED) 2011 International Symposium on*. IEEE, 2011, pp. 339–344.

[11] J. Ku, R. Mraz, N. Baker, K. Zakzanis, J. Lee, I. Kim, S. Kim, and S. Graham, “A data glove with tactile feedback for fmri of virtual reality experiments,” *Cyberpsychology & Behavior*, vol. 6, no. 5, pp. 497–508, 2003.

[12] D. Salle, F. Gosselin, P. Bidaud, and P. Gravez, “Analysis of haptic feedback performances in telesurgery robotic systems,” in *Robot and Human Interactive Communication, 2001. Proceedings. 10th IEEE International Workshop on*. IEEE, 2001, pp. 618–623.

[13] C. Collins, “Tactile television-mechanical and electrical image projection,” *Man-Machine Systems, IEEE Transactions on*, vol. 11, no. 1, pp. 65–71, 1970.

[14] W. Zhang, G. Kantor, and S. Singh, “Integrated wireless sensor/actuator networks in an agricultural application,” in *Proceedings of the 2nd international conference on Embedded networked sensor systems*. ACM, 2004, pp. 317–317.

[15] R. Rusu, B. Gerkey, and M. Beetz, “Robots in the kitchen: Exploiting ubiquitous sensing and actuation,” *Robotics and Autonomous Systems*, vol. 56, no. 10, pp. 844–856, 2008.

[16] A. Lapadatu, D. De Bruyker, H. Jakobsen, and R. Puers, “A new concept for a self-testable pressure sensor based on the bimetal effect,” *Sensors and Actuators A: Physical*, vol. 82, no. 1, pp. 69–73, 2000.

[17] A. Cozma and R. Puers, “Electrostatic actuation as a self-testing method for silicon pressure sensors,” *Sensors and Actuators A: Physical*, vol. 60, no. 1, pp. 32–36, 1997.

[18] C. Perez, A. Santibanez, C. Holzmann, P. Estevez, and C. Held, “Power requirements for vibrotactile piezo-electric and electromechanical transducers,” *Medical and Biological Engineering and Computing*, vol. 41, no. 6, pp. 718–726, 2003.

[19] Z. Del Prete, L. Monteleone, and R. Steindler, “A novel pressure array sensor based on contact resistance variation: Metrological properties,” *Review of Scientific Instruments*, vol. 72, no. 2, pp. 1548–1553, 2001.