

# Using Piezoelectric Materials for Wearable Electronic Textiles

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## Abstract

*An open issue for electronic textiles (e-textiles) used for wearable computing is the choice of materials. This paper describes the desirable characteristics of piezoelectric materials for wearable e-textiles, including shape sensing, sound detection, and sound emission. The paper then describes an initial prototype of a glove for user input that employs piezoelectrics to sense the movement of the hands to illustrate the design issues involved in using piezoelectrics.*

## 1. Introduction

Ideally, wearable computing devices provide computational capability and also function as the clothing being worn, such as a sport jacket that can also monitor a heartbeat. Electronic textiles (e-textiles), fabrics that contain electronic or computational devices, are perfectly suited to creating these dual-role devices. The primary challenge in electronic textiles is to find materials and devices that provide the desired functionality and that can be easily meshed into hybrid materials. Piezoelectric materials offer significant promise for e-textiles applications. Piezoelectric materials have a number of useful features and are available in a variety of form factors with reasonable cost and development complexity. This paper discusses the properties, advantages, and design aspects associated with piezoelectric materials as well as a case study demonstrating their use in a shape-sensing role.

## 2. Previous Work

The two areas of research most closely related to the work described in this paper are e-textiles and glove-based user interfaces.

## 2.1. E-textiles

Despite being relatively new, e-textiles have been created for and applied in a variety of applications such as antennas built into battle dress uniforms [1], an MP3 player embedded in an article of clothing [2], and roll-up LCD displays [3]. These applications use several different types of materials including conductive threads, conductive films, and liquid crystals that can be applied like paint. STRETCH, a DARPA-funded project at Virginia Tech, is using multiple discrete components and piezoelectric films to build an acoustic array incorporated into a multilayer fabric for the purpose of detecting and locating large moving vehicles. Other research projects have successfully incorporated conductive fibers into e-textiles. Metallic organza has been used in both the “row and column fabric keyboard” and the “musical jacket with embroidered keypad” [4]. The keyboard uses direct electrical connections while the keypad on the jacket utilizes capacitance change as a sign of pressing a key. The Sensate Liner (SL) is an example of a system where the interconnections are inherent in the fabric [5]. The main purpose of the interconnections is the detection of bullet penetrations. Additionally, the system also offers connections to other discrete sensors for further medical monitoring. Georgia Tech’s Wearable Motherboard can be used as a PAN (Personal Area Network) in which the devices that are carried by the user can interact and share data [6].

## 2.2. Glove-based user interfaces

Previous attempts at creating an alternative data input device for the hand have used a variety of detection methods. Some of these detection methods have included air pressure, light, and

biological capacitance. The first method utilized air hoses extending the length of the fingers, measuring position based on the increasing or decreasing pressure in each hose [8]. This rate of increase/decrease was then correlated to a rate of finger position change based on the mechanical properties of the finger. The resolution of the device was claimed to be roughly one degree of movement. The disadvantages of this method include bulk and leaking air hoses.

The second method detected finger motion via the disruption of a beam of light extending from the wrist [9]. Additional motion was detected via accelerometers. Disadvantages of this method include sensitivity to lighting conditions, durability of the light-emitting system, and cost. Specific results of this device were not mentioned.

Another method was the detection of finger movement and position based on changing wrist capacitance, as used in the Sensaboard<sup>®</sup> [10] and in the development of a virtual number keypad [15]. The Sensaboard<sup>®</sup>, despite being considered for commercial production, did not fare well in demonstrations. The virtual number keypad, however, boasted an accuracy rate of nearly 78 percent. It is important to note that the complexity of a matrix keypad, in terms of required movements, is significantly less than that of a QWERTY keyboard. Drawbacks of this technique include significant variations in individual wrist capacitances and the complexity of processing algorithms.

### 3. Piezoelectric Materials for E-textiles

Piezoelectric materials are well matched to the needs of e-textiles and wearable computing, offering low power consumption, a choice of form factors, and components with multiple uses. A unique property of piezoelectrics is their ability to produce a broad range of voltages, from tens of millivolts to hundreds of volts based on the type and magnitude of the applied stimulus. Piezoelectrics respond to almost any type and magnitude of physical stimulus, including but not limited to pressure, tensile force, and torsion. Piezoelectrics do not have a minimum requirement for producing a response. Their ability to detect the type and magnitude of the

stimulus is limited only by the sensitivity of the interface and any contributing environmental variables. One wearable computing application embedded a piezoelectric in the sole of a shoe such that walking motion could be used to generate power [7].

Given the lack of e-textile applications incorporating piezoelectric materials, we spent a significant amount of time investigating their properties and characteristics. Some of these tests included the comparison and observation of voltage responses for embedded and non-embedded piezoelectric films, sound generation while under stress, and analysis of voltage responses for various types of stimulation. One of our prototypes, a piezoelectric film strip woven into a piece of fabric, is shown below in Figure 1.

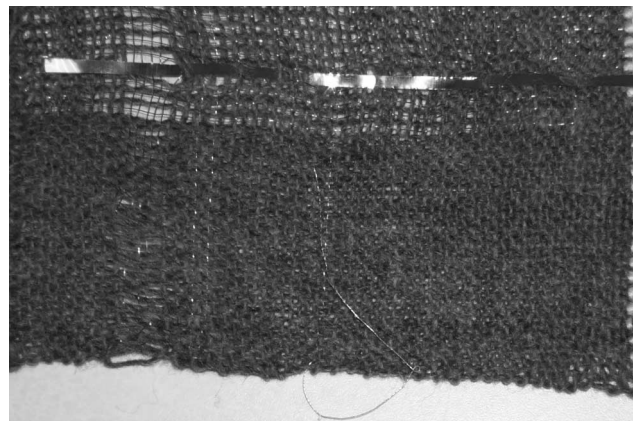


Figure 1. Woven piezoelectric film strip

Piezoelectric materials also exhibit a duality between physical motion and electric charge. When a voltage is applied to a piezoelectric, the crystalline structures produce motion causing a deflection of  $25 \times 10^{-12}$  meters/volt in typical piezoelectric films [12]. For an input signal having sufficient shape, magnitude, and frequency response within the auditory limits of humans, the materials vibrate, producing an audible tone.

While piezoelectrics can be used to create sound, they also respond to sound, just as they would any other physical stimuli, by producing a corresponding voltage response. This property allows piezoelectrics to be used as efficient microphones or basic sound detection devices. We tested this property for a number of widths of several piezoelectric materials. The power

spectral density for a ¼ inch wide strip of piezoelectric film in response to a 3kHz sine wave is shown in Figure 2. From the illustration one can see the concentration of power at 3kHz and the noise from 60Hz devices that were near the testing area.

Piezoelectrics are available in a variety of form factors including co-axial cable, film (laminated and un-laminated), paint, and thread, allowing creativity when embedding piezoelectrics within other types of materials.

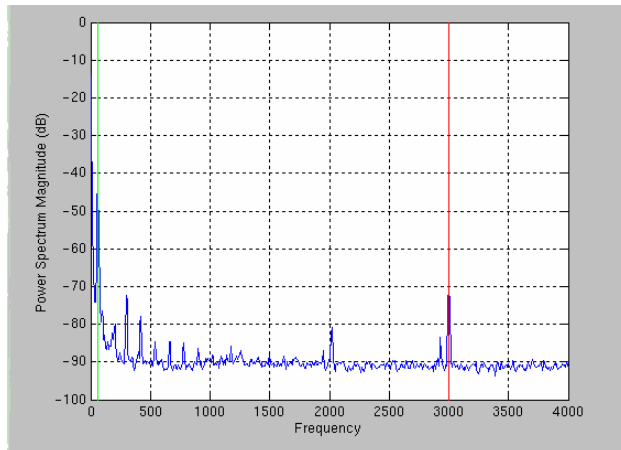


Figure 2. Power spectral density for piezoelectric film strip

#### 4. Design Preliminaries & Theory

To demonstrate the design issues involved in the application of piezoelectrics, we now describe the development of a glove utilizing piezoelectrics as shape sensors. The primary function of the glove was to detect the user's typing motions, allowing the glove to replace a keyboard. The design issues we encountered in this particular application are representative of other e-textile applications incorporating piezoelectrics.

For this initial prototype, several assumptions were made. The definition of a keyboard was limited to thirty keys on the three rows of a standard QWERTY keyboard that contain the alphabet. The row of numbers was not included. Other keyboard layouts such as the Dvorak keyboard or letter-frequency keyboards were not considered. Additionally, it was necessary to assume that the user would type using standard typing kinematics. Any deviations from the

standard touch-typing model were not accounted for in the design.

Aspects that required analysis prior to the design of the glove itself were the biological considerations and kinematics of the standard typing motions. Specifically, the goal was to identify the minimal number of motions required to model the motion of the fingers. Through careful observation, it was possible to generalize the motions of the hand as follows. The human hand consists of two major joint systems, the mid-finger and lower. The movement and shape of the upper half of the fingers is dictated by the mid-finger joints. For most individuals, movement of the uppermost finger joint is entirely involuntary and bends at a rate nearly proportional to the mid-finger joint. Thus we assume that the flexing of the fingers is controlled entirely by the mid-finger joint. The lowest set of joints, commonly known as the knuckles, is what allows the hand to close into a fist shape as well as perform the grasping motion. It is important to note that the flexing of one or more of these joints causes involuntary movement of other non-flexing fingers. The next important motion of the hand to analyze is lateral movement along the hand-plane. Two of the five fingers, the pointer finger and the pinky, possess significant lateral deviation. The third and final type of hand motion is the special case of thumb movement. The thumb's movement rotates about an imaginary axis running through the base of the thumb to the center of the wrist. To fully detect typing movements, the glove must be capable of detecting the relative flexing of the mid-finger joint as well as the stroke of a key.

Piezoelectric films were used to sense these flex and tap (pressure) motions of the user's hands. The choice of piezoelectrics as shape sensors stems from their excellent motion sensing capabilities and their unique characteristic of having both a positive and negative voltage response for a given stimulus. The ability to detect the direction of motion results from the differing magnitudes of the positive and negative voltage responses. For a particular direction of motion, the portion of the response corresponding to that direction was 0.5 – 2.0 times larger than the response in the opposite direction. Because the finger was moved in the “negative” direction,

the negative section of the response was roughly two times larger than the positive section. This behavior is illustrated in Figure 3. In addition to being larger, the portion of the response corresponding to the direction of motion also occurs first.

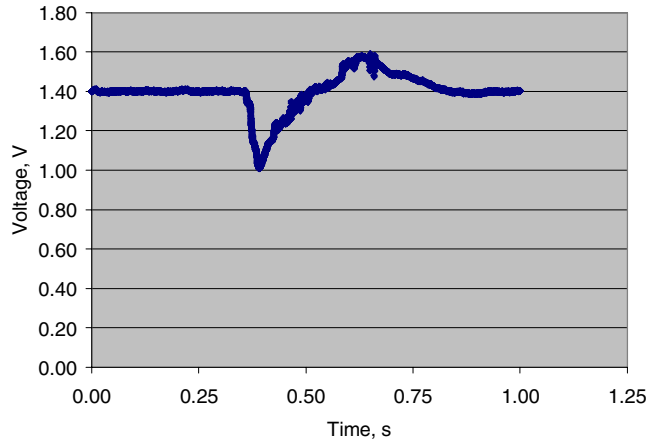


Figure 3. Flex voltage response

The differentiation between a keystroke and a finger flex was achieved by observing the relative magnitudes of the resulting voltage responses. The magnitude of the tapping motion was about five times larger than that of a flex motion as shown in Figure 4.

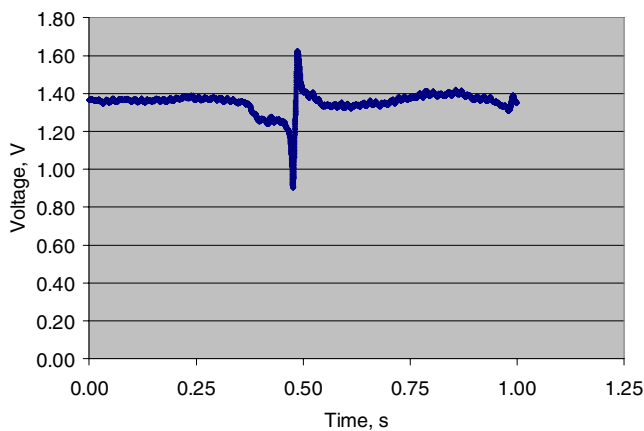


Figure 4. Tap voltage response

As described in the previous-work section, several alternatives exist for sensing these types of motions, including accelerometers, mechanical models, capacitance monitoring, and light sensors. None of these options, however, offers

the simplicity, functionality, and cost effectiveness of piezoelectric materials. Table 1 offers a brief summary of the *relative* advantages and disadvantages of each motion-sensing option with respect to its peers. The rankings for the form factor rating are based on ease of incorporation, ubiquity, and number of form factors available. Each alternative was also categorized by the type of motion it could detect. The ratings for power requirement and cost were generated by grouping each alternative in three levels: low, moderate, and high.

	Piezos	Accelerometers	Mechanical	Light	Capacitance
Form Factor Rating	1	4	5	3	2
Sensible Motions	All	All	Axial	All	Axial
Power Req	Low	Moderate	Low	High	Low
Cost	Low	Moderate	High	High	Low

Table 1. Shape sensing materials comparison

In addition to providing the capability for distinguishing motions, piezoelectrics are simple to interface with additional devices. Because the response of a piezoelectric is similar to a high-impedance AC source, the resulting analog signal can be processed or the signal can be digitized using an A/D converter. If the signal is digitized, the data may be manipulated by any number of digital devices and/or logical operations. If the analog signal is processed, a number of operations may be performed on it, including phase shifting, transformation, and amplification. The high output impedance AC source characteristic of piezoelectric films produces significant voltage output for little movement. In terms of our application, the voltage output varied from 300mV to 1.5V; for applications with higher magnitude stimuli, however, the voltage range produced could be in the hundreds of volts.

When interfacing with piezoelectric materials, several considerations must be taken into account. The first major consideration is the effect of coupling capacitance on the output voltage levels. When piezoelectric films contact the user's body, capacitive coupling occurs between the body and the piezoelectric film. This results in a small DC bias (hundreds of millivolts) in the output voltages of the films. This bias will vary depending on environmental conditions and the user. The second major consideration is the method and type of connections to the piezoelectrics. Careful construction practices and

the minimization of wire length must be used to avoid noise and interference.

The selection criteria for our choice of films were based on our desire to detect and distinguish between tap and flex motions of the hands without impacting the flexibility of the glove. Generally the selection of the type of piezoelectric material depends on the requirements of the application. The optimal choice of piezoelectric(s) may be of any form factor (films, co-axial, paint, etc.) or a combination thereof. This choice is typically determined by simulating use and analyzing the resulting data. Given our choice of films, it was necessary to choose between the various form factors. The methodology used to determine which type of piezoelectric film best fit our application involved testing and analyzing the flex and tap response of both the laminated and un-laminated films embedded in a two-layer fabric glove. The un-laminated films, having the consistency of ultra-thin aluminum foil, provided reasonable tap responses but did not have enough rigidity to produce any results in the flex test. The un-laminated films exhibited the best production of sound and response to sound, but this was not a necessary function for our device. The laminated films, when subjected to the same tests, produced excellent tap and flex responses, but did not respond as well to sound.

Another important aspect of piezoelectric films was discovered when both types of films were cut into varying sizes and retested. The magnitudes of the responses were proportional to the surface area of the films. This is an important consideration when deciding on the configuration and placement of the film sensors. After completion of the testing, it was determined that laminated films provided voltage responses and durability that were closest to the needs of our application. The two specific types of piezoelectric film sensors that were used were LDT0-028L and LDT1-028L [12] from Measurement Specialties Inc [13].

## 5. Glove Design

The design of the glove and its support system began with the arrangement of the piezoelectric film sensors. The locations of the sensors were

based on the earlier analysis of hand kinematics during typing. The sensors were placed at the mid-finger joint, the fingertips, and the exterior side of the index finger (not shown), as depicted in Figure 5. Other sensor configurations, such as sensors extending the length of the fingers, were considered. However, to reduce cost and provide maximum dexterity, the amount of finger surface area covered by the sensors was minimized. Also, full-length sensors would be difficult to place without having unwanted flexing of the film and unintended side-effects on finger motion.

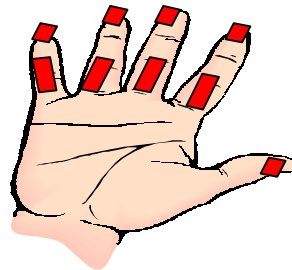


Figure 5. Sensor arrangement

The mid-finger sensors detected vertical flexing of the finger, the fingertip sensors detected taps, and the additional sensor located on the index finger detected lateral movement. With sensors at these locations, all required typing motions could be observed.

The fingertip and mid-finger sensors for each finger were each connected to a single channel on an A/D converter [14]. The A/D converter was controlled by a Motorola HC12 microcontroller that collected and packaged the conversion data into two-byte packets for processing at the PC level. A block-diagram schematic of the system is shown in Figure 6. The packets contained a single hand identifier bit, three channel identification bits, and twelve bits of conversion data. The data packets were then sent to a PC via the serial port and processed using algorithms written in C++ for purposes of experimentation.

The primary software model used to process the incoming data was based on a state machine. Given the confines of our defined keyboard, each finger could assume a finite number of positions. For fingers other than the index finger and thumb, the number of possible states is three: upper row, home row, and lower row. The special cases of the index finger and thumb could exist in six

states and one state, respectively. The index finger could assume positions in the upper, home, and lower states as well as two lateral positions, each containing three keys. The thumb had one constant positional state and was only concerned with a tapping motion that indicated the insertion of a space. Given the state information and the channel, it was possible to map each state of the system to its corresponding letter value when a keystroke event was detected. Each finger could change states only if a flex motion was detected. The first task of the processing mechanism was to filter the incoming data from the microcontroller via three sets of thresholds. These thresholds defined the upper and lower voltage ranges of particular events as well as the acceptable ranges of the bias voltage. If a sampled value fell between or above these thresholds, then it became an event candidate passed along for further processing.

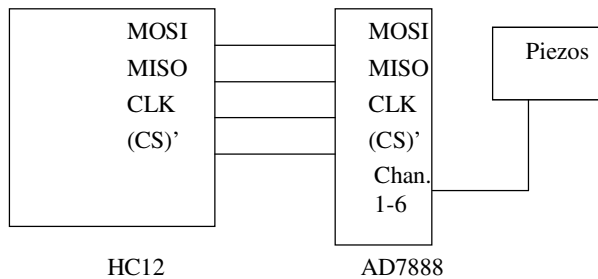


Figure 6. System block diagram

The determination of these thresholds was achieved mainly through a process of trial and error, but was ultimately limited by what one would consider normal use. For high enough threshold values, the samples that exceeded these thresholds were almost certain to be the results of a tap or flex event, because significant excitation of the piezoelectric sensors would be required to obtain a voltage of those magnitudes. To further assure that almost all of the appropriate values were filtered by the thresholds, several samples of data were taken and statistically analyzed to produce a 99.9% confidence interval. Thus we could be certain that 99.9% of the appropriate values would be filtered, assuming that the number of serious anomalies was low. Although these thresholds may vary among users with different typing speeds and styles, they may be

easily adjusted by modifying the threshold value or having the user participate in a training session. If the thresholds were left unadjusted, the accuracy of the device would suffer. However, the user might be able to adapt to a static threshold with little effort. Assuming consistent production methods and sources of the piezoelectric films used, the thresholds should not vary significantly from glove to glove

Two main approaches to analyzing event candidates were examined. The first method was to accept an event candidate as an event without further scrutiny. With this method, sampling anomalies caused erroneous output. Specifically, the anomalies took the form of values from the A/D converter that were significantly higher than the thresholds when no intended events had occurred. These anomalies are most likely attributed to errors caused by serial communication or noise from other portions of the system. To circumvent this problem more robust processing algorithms were designed. The second method kept a memory of the last six samples and searched for a pattern where a higher or lower sample point was bounded by two lower or higher sample points that were within the filtering thresholds. Data that exhibited this pattern indicated that a sample was taken from the maximum or minimum portion of an input, namely the voltage response of a stimulated piezoelectric sensor. This method greatly improved the accuracy of the device in differentiating between tap and flex motions as well as filtering sampling anomalies. An illustration of the thresholds is shown in Figure 7. The inner pair of lines allowed for variations in the bias voltage. The outer pair filtered out any set of samples whose magnitude was not large enough to be considered an event. Notice that despite having both a positive and negative response, only the larger portion associated with the intended motion will have enough data points above the threshold to be considered an intended action. The software module included an additional threshold for differentiating tap and flex motions via their response magnitudes.



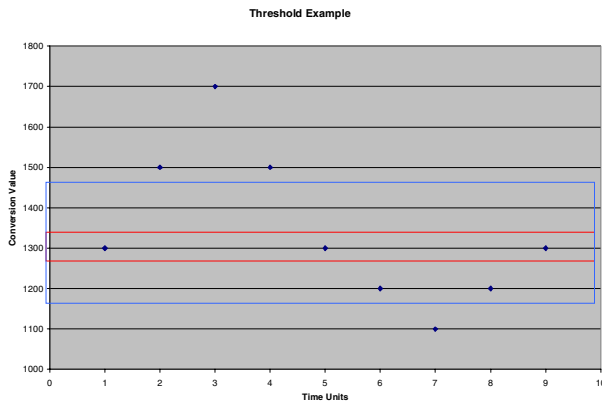


Figure 7. Threshold illustration

Once an event was detected, the appropriate actions were taken. If a flex motion occurred, the state of the corresponding finger would change to the state dictated by either the positive voltage response that corresponded to an upward movement or a negative response that corresponded to a downward movement. In the context of typing, a flexing finger precedes a keystroke except in the case of the home row. Thus when a transition from the home row or transition from upper row to lower row was detected, the software then ignored data from other channels and waited for the keystroke. This helped eliminate state transitions caused by involuntary finger movements associated with typing motions. When a tap was finally detected, the channel and state information were mapped to the appropriate output letter. If activity occurred on the index finger, then it was necessary to process another full set of cycles so that the lateral movement of the index finger, which occurs simultaneously with any vertical flexing, could be determined.

## 6. Future Work

Our prototype was built to produce data that could verify and support the feasibility of using piezoelectrics in both e-textiles and wearable applications. Avenues for further work include fully embedding the system, adding a wireless transmission facility, and refining the data collection process and associated algorithms.

While the initial prototype we have described used piezoelectric materials to sense the motion of the user, e-textiles using piezoelectric materials

offer the possibility of replacing discrete components employed in state-of-the-art wearable systems. For example, the tactile display described by Gemperle et al. [11] used discrete pager vibrators to stimulate the user's sense of touch. Piezoelectric films woven into a fabric could provide the same functionality. Similarly, the discrete microphones used in the wearable phased array described by Basu et al. [16] could be replaced by piezoelectric materials that are intrinsic to the cloth. Because of the multiple functionalities of piezoelectric materials, multiple types of discrete components could be replaced.

## 7. Conclusions

Piezoelectric materials provide a set of functions and characteristics unmatched by other currently available e-textile materials. This makes piezoelectrics not only valuable to the wearable computing community but also demonstrates a need for increased consideration concerning their use and investigation. Our particular case study not only demonstrated a valid approach to a wearable data entry device, but also demonstrated the uniqueness and advantages of piezoelectric e-textiles.

## Acknowledgements

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