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Abstract

Measuring the pressure in the shoe of an athlete performing his or her sport provides valuable insight to the unique characteristics of the behavior of the foot with regard to pressure applied versus the performance of the athlete.

This paper discusses sensor design and lead attachment when using piezoelectric film as a pressure sensor for in-shoe measurements. The sensor employed uses the Crossbow MICAz node and TinyOS. Experimental results are presented with regard to sensor design, lead attachment and in-shoe pressure measurement.

Though hindered by crosstalk, the results show that piezoelectric film sensors are useful in this context.

Contents

1 Introduction

Measuring the pressure in the shoe of an athlete performing his or her sport provides valuable insight to the unique characteristics of the behavior of the foot with regard to pressure applied versus the performance of the athlete. This could be used to optimize the running technique of the athlete and to foresee injuries [1].

Measuring the pressure must be performed without obstructing the athlete. The approach taken in this paper is to evaluate the use of piezoelectric film in this context through experiments placing it inside the athlete's shoe. The film will be used in conjunction with the Crossbow MICAz nodes which are small enough to be attached to the shoe or leg without hindering the performance of the athlete. Readings are sent using wireless radio to a base station at which data is collected and where further data processing can be performed.

Piezoelectric film has been used for other applications, e.g. energy harvesting for powering small devices by the energy generated when walking [4]. This was based on several layers of piezo film and takes advantage of the bending of the film. In direct relation to in-shoe pressure-measurement [6, 7] provide valuable insights with regard to especially stress on the plantar of the foot.

The contributions of this paper are twofold:

1. considerations of the sensor design are presented, discussed and evaluated, especially with regard to lead attachment
2. limitations of using the Crossbow MDA300CA ADC due to crosstalk when employing multiple sensors are discussed

This paper is organized as follows: first the characteristics of both the running motion of athletes and piezoelectric film are described, setting the context for in-shoe pressure measurement. Next, different designs of the sensor are discussed, after which the technical platform of the experiments is described. The experiments evaluate the sensor design and the results are presented and discussed, followed by a number of points to consider for future work. Finally, a conclusion will sum up the work done in the course of the six weeks during which this project was performed.[1]

2 Running motion

When running, the legs perform a cyclic action. One foot lands on the ground and the forward motion leads to the foot passing beneath and behind the body, after which it leaves the ground and moves forward to prepare for the next landing. In [3, p. 406-410] three phases are described, formalizing the motion of the foot while running:

- a *supporting phase* that begins when the foot lands and ends when the athlete's center of gravity passes forward of it

[1] This paper documents work conducted from 15 July 2005 to 26 August 2005 at the Computer Laboratory, University of Cambridge as part of the Embedded WiSeNts student mobility program. The work was performed under the supervision of Dr. Marcelo Pias and Professor George Coulouris and contributes to the Sentient Sports Project.

- a *driving phase* that begins as the supporting phase ends and ends as the foot leaves the ground, and
- a *recovery phase* during which the foot is off the ground and is being brought forward preparatory to the next landing.

During the *supporting phase*, the effects of the downward motion of the athlete, caused by gravity, is minimized by ensuring that the motion of the foot is in the backward direction. The effect of having the foot travel in the forward direction on impact with the ground would be a backwards force from the ground, due to Newton's first law, thus degrading the forward motion of the athlete. Having a vertical motion of the foot would be neutral with regard to the effect on the forward motion, while the backward direction, as mentioned, is preferable as this would lead to a forward motion from the ground.

The ideal backward motion when the plantar touches the ground would thus be to land with a backward motion, instituted by first landing on the front side of the foot. Most, but not all, athletes will eventually have the heel touch the ground as a part of the foot touching the ground.

The individual style of the athlete is also dependent on the type of sport performed. In the context of short-distance running, the initial impact on the ground is on the high ball (joints of the little toe) for 100 meter and 200 meter runs, while athletes running 400 meters, running at a slower pace, touch the ground further back, closer to the heel[3, p. 407].

The *driving phase* leads to the next stride. This is done by thrusting downward and backward against the ground, thus resulting in the forward and upward direction of motion for the athlete's body.

Finally, the *recovery phase* involves bringing the athlete's foot forward from behind to beyond the center of gravity. This is obtained by having the thigh rotate, first slightly backwards and then forwards, about the axis of the hip joint. When the thigh reaches a (near-)horizontal position the lower leg swings forward and the whole limb begins its descent to the track.

3 Piezoelectric film

The idea of using piezoelectricity as a pressure sensor is to use the electrical charge generated when polyvinylidene fluoride (PVDF) film is deformed on impact, i.e. pressed, bent, etc. The measured voltage is proportional to the applied force in an area of the film[5, p. 15]. We will be using Piezo Film Sensors from Measurement Specialties, Inc. These come in different sizes and thicknesses to fit the application at hand. The physical dimensions and properties of the films available to us are listed in Table 1 and the films are shown in Figure 1.

Piezoelectric materials are anisotropic, meaning that the response to pressure will be dependent on the axis on which the pressure is applied, cf. Figure 2 [5, p. 29]. As we will be applying pressure on the thickness of the film, i.e. the third axis, the piezoelectric coefficient used in the following equations is g_{33}[2].

[2] The first coefficient refers to the electrical axis, and the second to the mechanical axis. The electrodes will be placed on the top and bottom of the film, as this is the only practical position. Thus the electrical axis is g_{3x}.

9 μ	PVDF poled, golded on both surfaces, size 3cm by 3cm
28 μ	PVDF poled, golded on both surfaces, size 5cm by 5cm
52 μ	PVDF poled, golded on both surfaces, size 5cm by 5cm
110 μ	PVDF poled, golded on both surfaces, size 5cm by 5cm

Table 1: Physical dimensions and properties of the piezoelectric film.

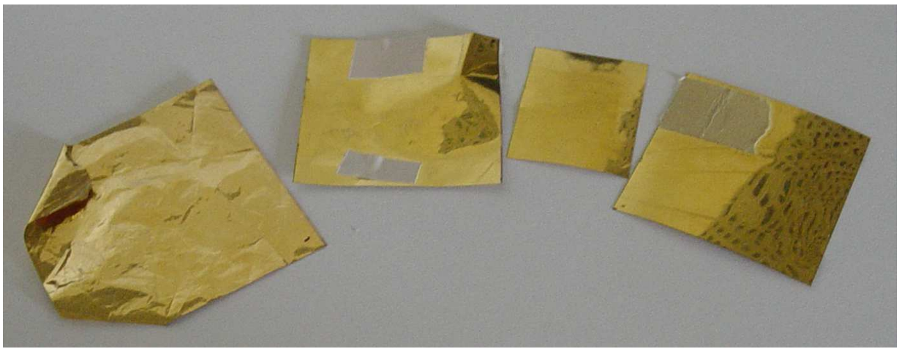


Figure 1: The four piezoelectric films, from the left: 9 μ, 28 μ, 52 μ (after having been cut for use in experiments) and 110 μ.

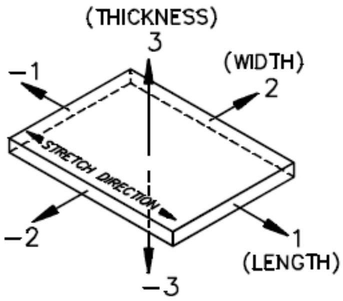


Figure 2: Numerical classification of axes [5, p. 28].

As the film will be affixed to a soft sole, it cannot be ignored that the two remaining axes will influence the values obtained, but this will not be accounted for in this initial design. The effects of the remaining axes will depend on the placement of the sensor, the pressure applied and the locality of the impact. A solution could be to laminate the film sensor, thus ensuring a rigid construction, but it will not be easy to impose this without being intrusive to the athlete using the shoe.

The properties of the output voltage, which can be measured using the technical platform described in Section 5.1.1, are as follows [5, p. 29]:

$$V_o = -g_{33} * X_3 * t \quad (1)$$

where $g_{33} = -339 * 10^{-3} \frac{V/m}{N/m^2}$
X_3 is load applied to piezo film in the third axis, measured in N/m^2
t is thickness of piezo film, measured in m

The unit of g_{33} is given by V/m, Volts out per meter of piezo film thickness, divided

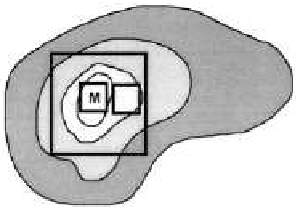


Figure 3: A schematic representation of one large and two small sensors positioned in close approximation to a localized peak pressure (M is the position of maximum pressure) [7].

by N/m^2, force applied to the relevant film area, respectively [5, p. 28]. Simple reasoning brings about the pressure as:

$$V = -g_{33} * X * t \Leftrightarrow X_3 = \frac{V}{-g_{33} * t} \quad (2)$$

Thus it will be possible to measure the pressure applied to the piezo film from the voltage and the thickness of the piezo film.

The preferred unit of foot-pressure measurement is kilopascals (kPa), thus converting from N/m^2 is a simple matter of dividing X_3 by 1000 when measurements are plotted.

There are several factors that determine the performance of the piezo film. These include changes in temperature and electrostatic sensitivity.

The typical operating temperature range for the PVDF is reported as -40 to +125°C [5, p. 26]. Experiments performed in [6] on temperature effects when using PVDF for in-shoe pressure measurement, suggest that the in-shoe operating temperature is expected to be 30 to 40°C. In [6] the variations of the PVDF performance are evaluated and discussed. With these evaluations in mind they conclude that the worst case scenario would introduce a maximum error of ∼2%. This is considered acceptable for our setup.

As this project has a limited time span we will be focusing on a crude implementation which can later be extended to a more robust solution. Thus problems with electrostatic sensitivity will be looked into and if possible minimized, but it will not be a prime objective when mounting the sensors. Ways of shielding the sensor should be considered in a future design.

4 Sensor design

In [7] it is recommended that "in-shoe sensors must be small, in order to be unobtrusive, yet durable enough to withstand the effects of humidity, temperature and bending". The size and placement of sensors greatly affect the measurements of pressure.

Soft-tissue contact surfaces have regions of high and low pressures. Figure 3 shows the performance of one large and two smaller sensors in such a scenario. The small sensor, placed in the M position, will have a good estimate of the real pressure value, while the second will report lower values for pressure. The larger surrounding sensor also covers areas of lower pressure and thus the output will be an estimate of the average pressure on this larger area.

In the design of a system for in-shoe pressure-measurement, a setup consisting of several small sensors is thus preferred over one or only a few large sensors. In [7] a minimum of 7 mm diameter of sensors is discussed, while [6] describes a 10 x 10 mm sensor.

Influenced by the above-mentioned details, our final design consists of a 10 x 10 mm PVDF sensor of 52 μ thickness. This is to be placed underneath the sole to avoid direct contact with the foot, which might lead to increased friction in this simple and unprotected design.

4.1 Lead attachment

The lead attachment is important as noise can be introduced if leads are not fastened appropriately. In [5, p. 8-12] several techniques with regard to lead attachment are described. These are grouped in penetrative and non-penetrative techniques. The penetrative include using rivets and attaching wires to these. Non-penetrative include using tape or low melting-point alloys (indium/tin/bismuth).

We have taken the approach of using the 3M #1245 EMI Embossed Copper Foil Shielding Tape as proposed in [5, p. 11][3]. The advantage of this approach is that if needed, we can solder on the leads to the tape before attaching it to the piezo film. Soldering the wire directly to the film could affect the performance of the film. Soldering does "appear to degrade the adhesive properties in the vicinity of the joint" [5, p. 11], but early experiments with this did not seem to be an issue.

The leads themselves are regular twisted pair leads obtained by taking apart a twisted pair network cable.

5 Experiments and results

After having determined the characteristics of the PVDF film, we now describe the setup and experiments which were performed in the evaluation.

5.1 Experimental setup

5.1.1 Hardware

The hardware on which the sensors are attached consists of the Crossbow MICAz[4] node with the Crossbow MDA300CA[5] data acquisition unit.

The MPR2400 (MICAz) node, see Figure 4, is the latest generation of nodes from Crossbow. The MICAz is based on the Atmel ATMega 128L processor and utilizes a Chipcon CC2420 radio which conforms to the IEEE 802.15.4 specification, thus allowing for transfer rates up to 250kbps.

The MDA300CA data acquisition unit is attached to the MICAz node and allows for up to eleven 12-bit ADC channels, see Figure 5. Of these we can use seven as single-

[3] Though a different, but similar, model

[4] See `http://www.xbow.com/Products/productsdetails.aspx?sid=105`

[5] See `http://www.xbow.com/Products/productsdetails.aspx?sid=77`

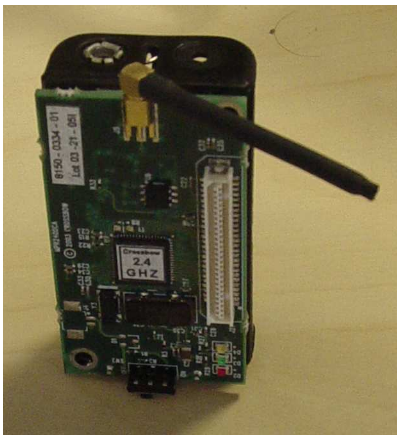


Figure 4: Crossbow MICAz node with battery pack attached.

ended analog channels (channels A0-A6) or three of these as differential analog channels (channels A11-A13). These channels support signals of a dynamic range from 0 to 2.5 V.

The remaining analog channels are differential precision analog channels with a dynamic range of ±12.5 mV and have too narrow a range for us to use without employing additional hardware to scale down the voltage.

Converting the 12-bit value obtained from channels A0-A6 and A11-A13 from the ADC into voltage can be done using [2, p. 25]:

$$Voltage = 2.5 * ADC\_READING/4096 \tag{3}$$

The only programming board that can fit the MICAz with the MDA300CA unit attached is the Crossbow MIB510[6] serial programming board. With this attached, software can be compiled and transferred to the MICAz using the serial port as described in the following.

5.1.2 Software

We used TinyOS[7] on the hardware platform. Crossbow provides a number of sample applications to be used with the MICAz, and specifically the `XSensorMDA300` application is provided for use with the MDA300CA data acquisition board.

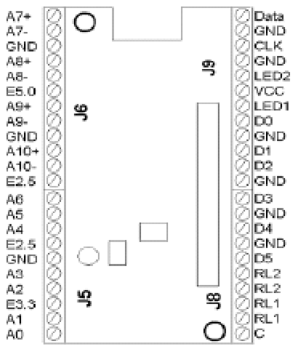
This sample application utilizes all channels, analog and digital, and also the built-in humidity and temperature sensors.

The sampling rate had a resolution of 0.1 s which was insufficient for our needs. This could be adjusted in source code, but with the additional code for buffer management, written for this general application, it was not directly usable. Thus, it was more convenient to specialize the sample acquisition as needed by our application. As we will only be using the analog channels, a custom-made application was developed, `TestPiezoFilmSensor`[8], which took the `XSensorMDA300` as its starting point for acquiring ADC data, but allowed for a sampling rate of 8 ms when using the UART and 12 ms when using the radio.

[6]See `http://www.xbow.com/Products/productsdetails.aspx?sid=79`

[7]See `http://www.tinyos.net`

[8]Source code mentioned in this report has been provided to the project supervisors.



A0 or A11+	Single-ended analog channel 0 or differential analog channel 11 positive side
A1 or A11-	Single-ended analog channel 1 or differential analog channel 11 negative side
A2 or A12+	Single-ended analog channel 2 or differential analog channel 12 positive side
A3 or A12-	Single-ended analog channel 3 or differential analog channel 12 negative side
A4 or A13+	Single-ended analog channel 4 or differential analog channel 13 positive side
A5 or A13-	Single-ended analog channel 5 or differential analog channel 13 negative side
A6	Single-ended analog channel 6
A7+ A7-	Differential analog channels 7
A8+ A8-	Differential analog channels 8
A9+ A9-	Differential analog channels 9
A10+ A10-	Differential analog channels 10
DATA	I2C Data
CLK	I2C Clock
D0 - D6	Digital Lines D0 to D6
C	Counter Channel
LED1	RED LED
LED2	GREEN LED
E5.0	5.0 V excitation
E3.3	3.3 V excitation
E2.5	2.5 V excitation
Vcc	Vcc of the Mote
RL1	Relay one sides (Normally-Open)
RL2	Relay two sides (Normally-Closed)

Figure 5: Pin configuration and assignments of the MDA300CA [2, p. 25].

Programming the MICAz consisted of attaching it to the MIB510 serial programming board which is connected to the serial port of the development computer. In Cygwin[9] the `TestPiezoFilmSensor` application is compiled and transferred using:

`make micaz install.`x `mib510,/dev/ttyS0`

where x is a unique identifier of the device in the network, e.g. `6`.

5.1.3 Acquiring data

In conjunction with the `XSensorMDA300` application, the `xlisten` program is provided by Crossbow. This program recognizes the data acquired from sensor nodes in the network, specifically it is possible to output data from a base station either directly attached using the serial port or using the Ethernet programming board (MIB600CA).

As the `TestPiezoFilmSensor` application is specialized for improved throughput, i.e. higher sampling rate, `xlisten` was modified slightly to correspond to this. The specific modification is to ignore messages with a length other than 18 bytes, which is the size of the message sent[10]. This was necessary as obscured messages appeared from time to time with a length other than 18 bytes. It has not been possible to find the source of this problem, thus ignoring these messages was a straight-forward solution. As messages are identified with a packet id, the failure to receive a given message can be detected in the data processing phase.

[9]The following is based on programming the MICAz using Cygwin and TinyOS. Other measures might be needed to perform this on Linux or other systems.

[10]This was done in `xserial.c` in the `xserial_port_read_packet` function

```
7e427d5e000088084d6c00b304b106aad183 [18]
```

Figure 6: Output from `xlisten`, packet id and three samples underlined.

To store the acquired data, `xlisten` is run in quite and raw modes:

`./xlisten -r -q >` *samplefile*

where *samplefile* is the file in which to store the sample data.

An example of the output obtained using `xlisten` is shown in Figure 6.

5.1.4 Data analysis in MATLAB

To allow for easy data analysis, simple MATLAB programs were developed to import and plot the raw data. Specifically, the arrays `sample1-3` contain the data with each row consisting of one packet. The `doPlotMovAvg` function takes the filename of the data acquired, the step size for the moving average, the start/end samples to plot and whether to generate EPS-files. This will import the data and plot it in independent subplots. Data readings are converted to voltage using the `adcSingleToV` function, which implements Equation 3. Setting the step size to 1 will plot the readings as recorded.

5.2 Experimental results

In the following, several experiments are described. The term *tapping* is defined as a short tap with the index-finger issued to the surface of the piezo film. When *holding*, the index-finger is held against the surface of the piezo film with a constant pressure – as best as possible. Unless otherwise noted, the piezo film sensor itself is fastened to a table using tape. The final design can be seen in Figure 7.

5.2.1 Determining maximum voltage

To get a feel of the piezo film and putting it in relation to the specification of the ADC, it is necessary to know the practical range of the voltage generated by the piezo film with respect to the pressure applied in our given context, namely the inside of the shoe. This is necessary in order to avoid burning the ADC. Thus, if it is above the maximum input of the ADC, it would be necessary to scale down the voltage by use of resistors. The measurements were performed using the HP 54645D mixed signal oscilloscope available at the Computer Laboratory, University of Cambridge.

The measurements in the different experiments can be seen in Table 2. These measurements were obtained by performing the described experiment multiple times until it was not possible to obtain a higher value within a reasonable time, i.e. 5-10 minutes.

As described in Section 5.1.1, the dynamic range of the ADC is 0 to 2.5 V. The measurements are in some cases, namely when tapping and bending, beyond these levels, but as these measurements were the extremes and did not represent actual behavior as can be expected in our context, no amplification or scaling down of the signal was found to be needed. However, we anticipate that scaling down may be required in a robust version of our sensors, to use the more precise differential channels.

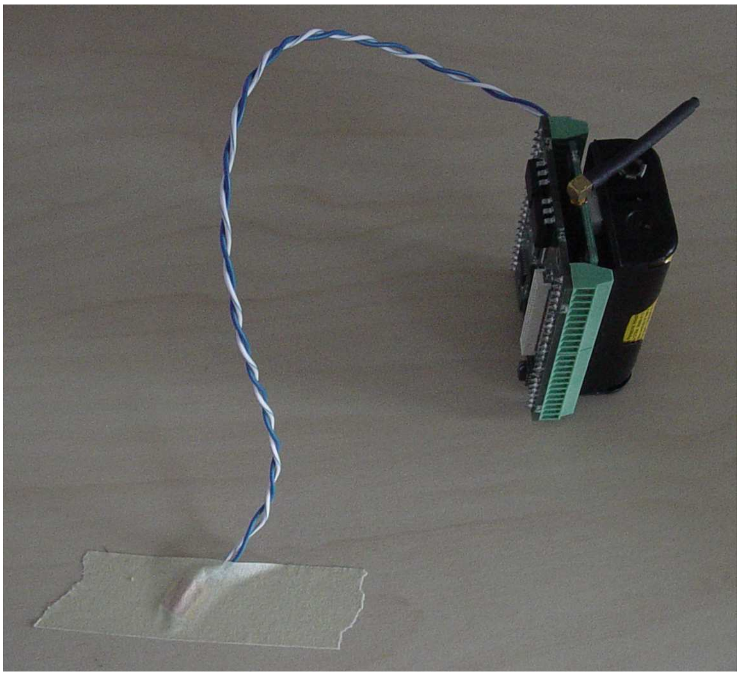


Figure 7: Final design, piezo film sensor, leads, ADC and MICAz.

Description	**Maximum voltage**	**Calculated Pressure**
Tap, finger	6.875 V	390.0 kPa
Tap, hammer	> 20 V	> 1134.6 kPa
Bend, smooth	843.7 mV	47.9 kPa
Bend, abrupt	2.906 V	164.9 kPa
In-shoe, no movement	118.7 mV	6.7 kPa
In-shoe, stamping	968.7 mV	55.0 kPa
In-shoe, jumping	843.7 mV	47.9 kPa
In-shoe, “running” [a]	375.0 mV	21.3 kPa

[a] Simulating the movement of a stride

Table 2: Maximum and minimum voltage of PVDF measured using oscilloscope.

With regard to in-shoe measurements, the piezo film was taped to the shoe under the in-sole. The length of the wires from the piezo film to the oscilloscope were several times the length of the tapping and bending experiments, which influenced the results. Though the length of the wire when mounted in the final design would not be of this length, it was still useful to get insight on the behavior of the film when placed inside the shoe. Especially, that the sole itself did not hinder the measurement of the pressure applied.

In [7] pressure ranges for standing, walking and extreme situations are discussed. These range from ~0-200 kPa and ~0-1000 kPa for standing and walking, respectively to ~2000-3000 kPa in extreme situations. These figures, in relation to Equation 1, give values that greatly exceed the measurements found using the oscilloscope, when performing tests with the 52 μ film.

The range is also quite different from the findings mentioned in [6]:

> Average peak vertical pressure under the main load-bearing portions of the foot's 2-4 MTH reported to be 420 kPa and it can be higher then 60 or 70 kPa under the heel.

These measurements are more in line with the measurements obtained using the oscilloscope as can be seen in Table 2. As mentioned, the length of the wire affected the results, thus it is expected to be even closer when we perform experiments in the shoe.

Although the HP 54645D oscilloscope provides storage functionality, it was not possible to use this, due to the lack of required equipment. Thus, the next step is to perform experiments with the piezo film sensor attached to the ADC to allow for data storage and analysis.

5.2.2 Lead attachment techniques

As mentioned in Section 4.1, lead attachment to the piezo film is important to avoid unnecessary noise, introduced by friction. To measure different attachment techniques, three experiments were conducted using the 3M #1245 EMI Embossed Copper Foil Shielding Tape:

1. Taping the lead directly to the piezo film sensor, in the following referred to as the *single-layer technique*

2. Placing a piece of tape on the piezo film sensor and on top of this taping the lead using a second piece of tape, in the following referred to as the *dual-layer technique*

3. Soldering the lead on top of the tape and afterwards placing the tape on the film, in the following referred to as the *soldering technique*

The experiments were performed using three different sensors cut to the size of 10 x 10 mm with the three above-mentioned lead attachment techniques, see Figure 8. As can be seen from the plots of tapping in Figure 9, the single- and dual-layer techniques have the same behavioral characteristics which is presumably due to some minimal friction compared to the tightly fastened soldering technique. It is interesting to see though, that performing the moving average on the plots leads to similar plots for all three sensors.

With this in mind and to ease further experiments, we adopt the single-layer technique.

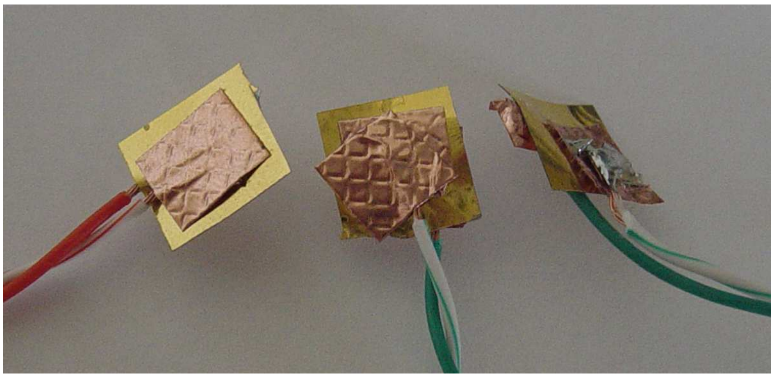
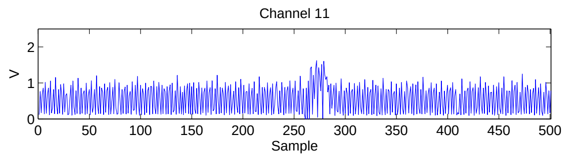
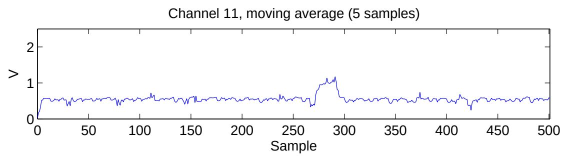


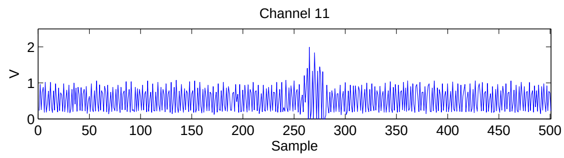
Figure 8: The three lead attachment techniques, from the left: the single, dual and soldering technique.



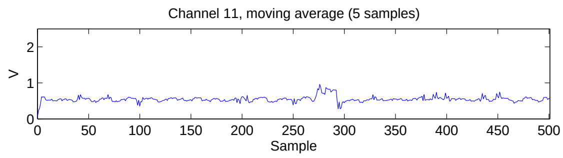
(a) Single-layer technique, tapping.



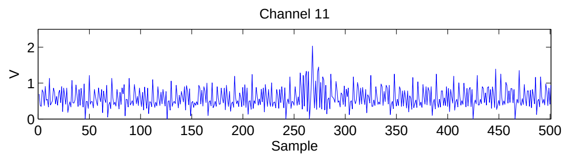
(b) Moving average using 5 samples.



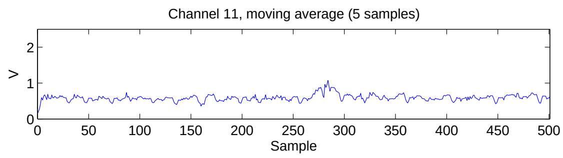
(c) Dual-layer technique, tapping.



(d) Moving average using 5 samples.



(e) Soldering technique, tapping.



(f) Moving average using 5 samples.

Figure 9: Comparison of lead attachment techniques.

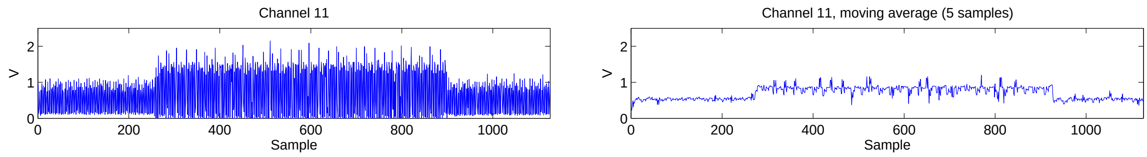
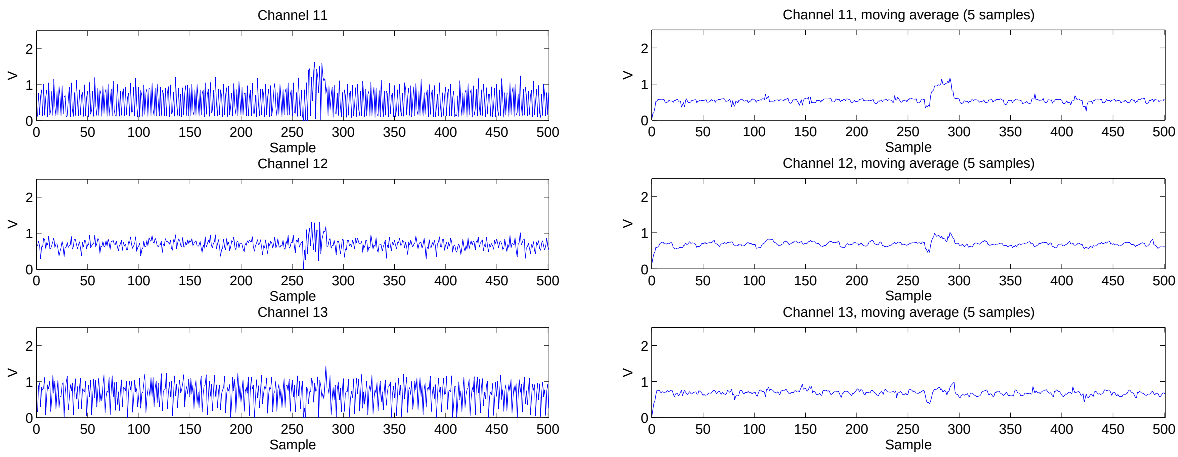


Figure 10: Result of long term pressure (holding), on the piezo film.



(a) Crosstalk on channel 12, minor crosstalk on channel 13.

(b) Moving average using 5 samples, crosstalk on channel 13 more clear.

Figure 11: 1 piezo film sensor attached to channel 11, tapping.

5.2.3 Characteristics of long term pressure

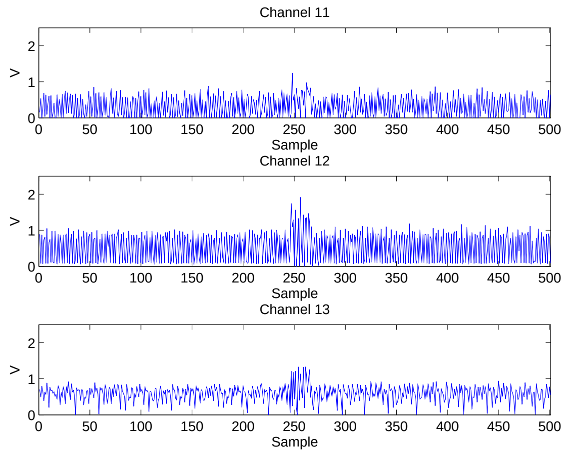
Though tapping is easy to detect, it does not correspond to the context in which the piezo film sensors will be used. When in-shoe pressure measurements are performed, the sensors will be subjected to relatively long periods of pressure as described in Section 2.

To simulate this pressure a simple experiment was performed where the piezo film was subjected to a longer period of pressure, i.e. holding the index-finger on the film, see Figure 10. As can be seen, the characteristics of the piezo film when holding results in a clear rise in voltage, thus pressure applied in-shoe should be easily measurable.

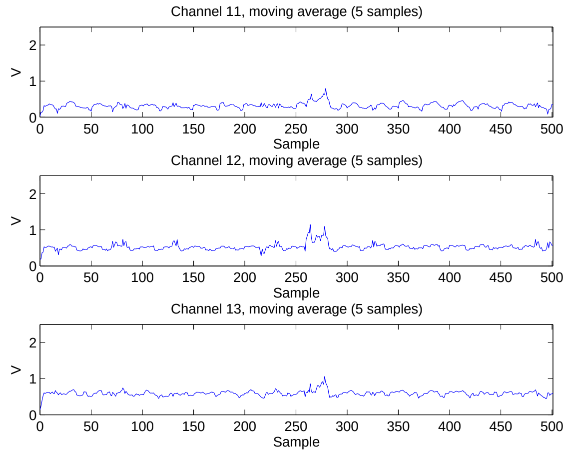
5.2.4 Crosstalk

Given the discussion in Section 4 regarding a few large sensors versus many small sensors, the next experiment utilizes three piezo film sensors. The results of connecting multiple sensors lead immediately to crosstalk as can be seen in Figures 11-13.

The problem of crosstalk is present in all three experiments, thus leaving a substantial problem to be solved. It has not been possible to filter out the crosstalk using MATLAB. The problem with the crosstalk as it appears is that there is no way of knowing if pressure measured on one channel is the result of real pressure on the piezo film or crosstalk from a different sensor being pressed. Furthermore, the problem is even more evident when multiple sensors are subjected to pressure concurrently as can be seen in Figure 14, thus making it impossible to deduce the real value of the pressure applied on the individual sensors.

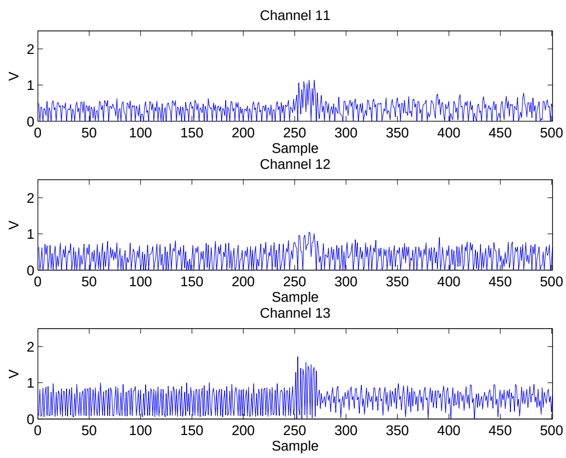


(a) Minor crosstalk on channel 11, crosstalk on channel 13.

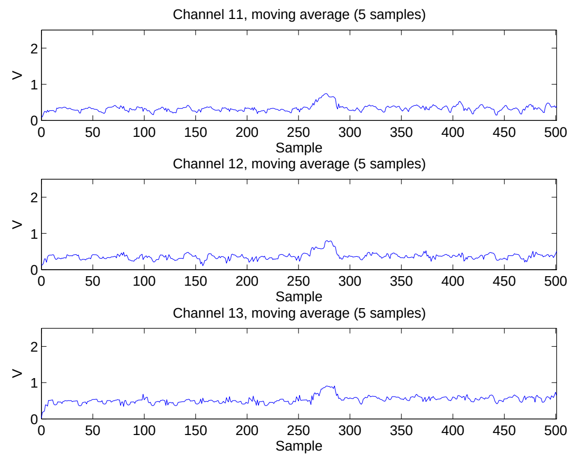


(b) Moving average using 5 samples, crosstalk on channel 11 more clear.

Figure 12: 1 piezo film sensor attached to channel 12, tapping.

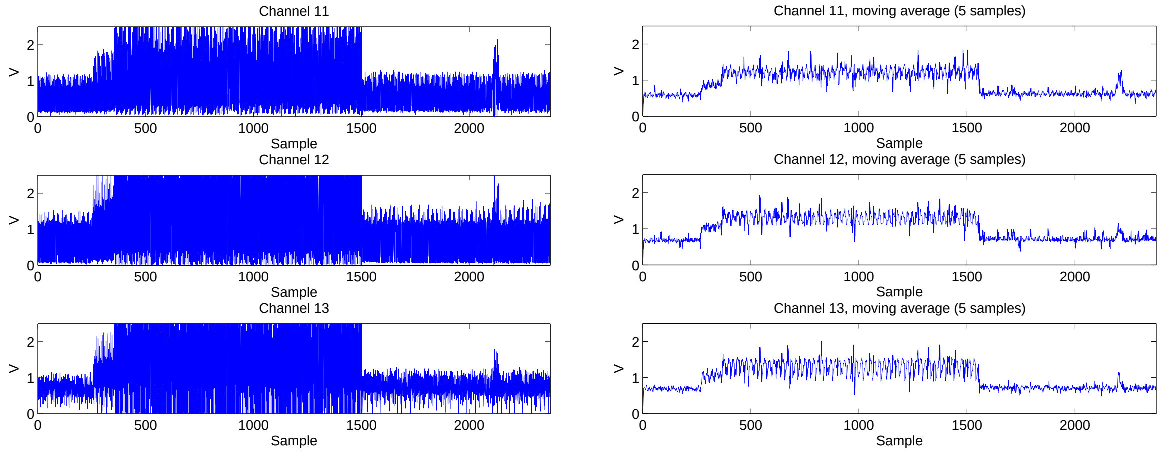


(a) Crosstalk on channels 11 and 12.



(b) Moving average using 5 samples.

Figure 13: 1 piezo film sensor attached to channel 13, tapping.



(a) Crosstalk from holding on channel 12.

(b) Moving average using 5 samples.

Figure 14: 2 piezo film sensors attached to channel 11 (tapping) and 12 (holding), respectively.

As can be seen in Figure 15 where three different film sensors are attached to channels 11-13, respectively, the noise is so predominant that the taps themselves are not easily recognizable.

After contacting Crossbow regarding this behavior, it was determined that this is standard behavior for the ADC. To test the effect of a constant energy source, as suggested by Crossbow, we performed a simple experiment with connecting a battery to channel 11 of the ADC. The energy measured on the battery before starting the experiment was 1.57 V and Figure 16 shows the result of the experiment.

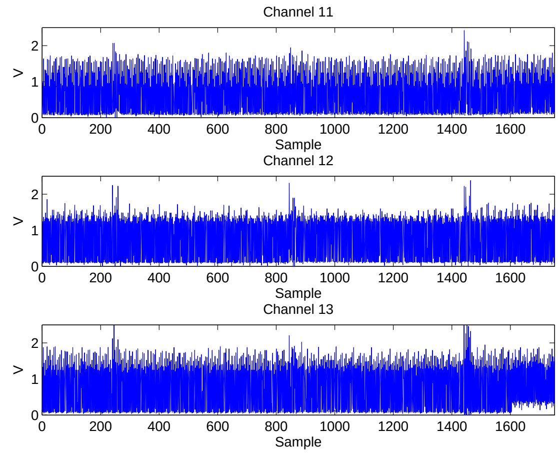
The ADC shows no signs of malfunction, thus the problem can be reported as crosstalk. As no sensors are connected to channels 12 and 13, comparing channel 11 to these shows that there is at least some crosstalk in this experiment as well, as the level of voltage measured on channel 12 (which is physically closer to channel 11 than channel 13 is) is consistently higher than that of channel 13.

Even though it severely limits the use of the project, it is necessary to limit the number of sensors to one in the following experiments, to obtain and calibrate the data. As will be discussed in Section 6, there are several techniques that could be employed to minimize this behavior, including the use of a multiplexor when sampling the sensors.

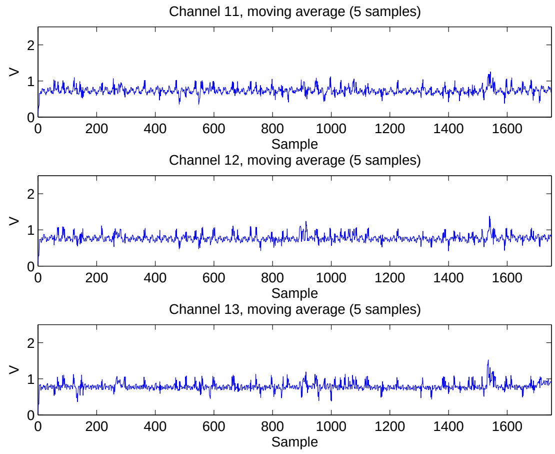
5.2.5 In-shoe pressure measurement

The final experiment is performed using a shoe with a removable in-sole. Here the piezo film sensor is attached underneath the in-sole using duct tape. A hole was drilled in the rear end of the shoe to allow the wire to be attached to the MICAz node, located outside the shoe as seen in Figures 17-18.

Experiments with the in-shoe pressure measurements were performed using the radio rather than the serial port. The smallest sampling rate obtained from the radio was 12 ms. To test the setup in real life experiments, two were performed: walking and running, respectively. Both experiments show clear spikes of the foot hitting the ground, see Figures 19-20.

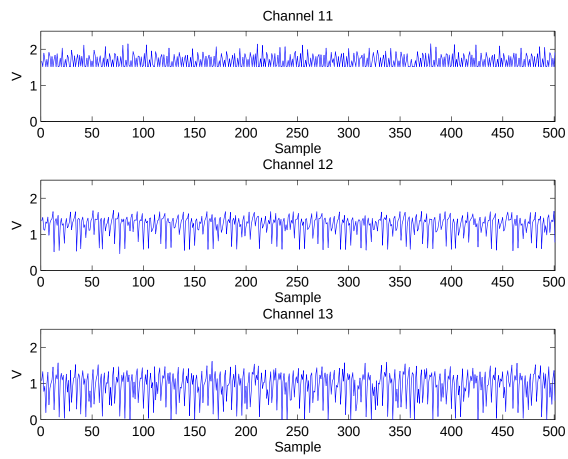


(a) Crosstalk on all three channels, taps not easy to differentiate from noise.

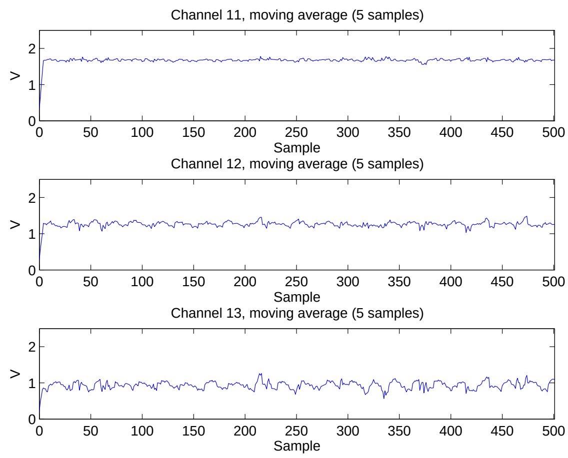


(b) Moving average using 5 samples.

Figure 15: 3 piezo film sensors attached to channels 11, 12 and 13, tapping one after the other.



(a) 1.57 V battery.



(b) Moving average using 5 samples, expected voltage level on channel 11.

Figure 16: To test if ADC is working.

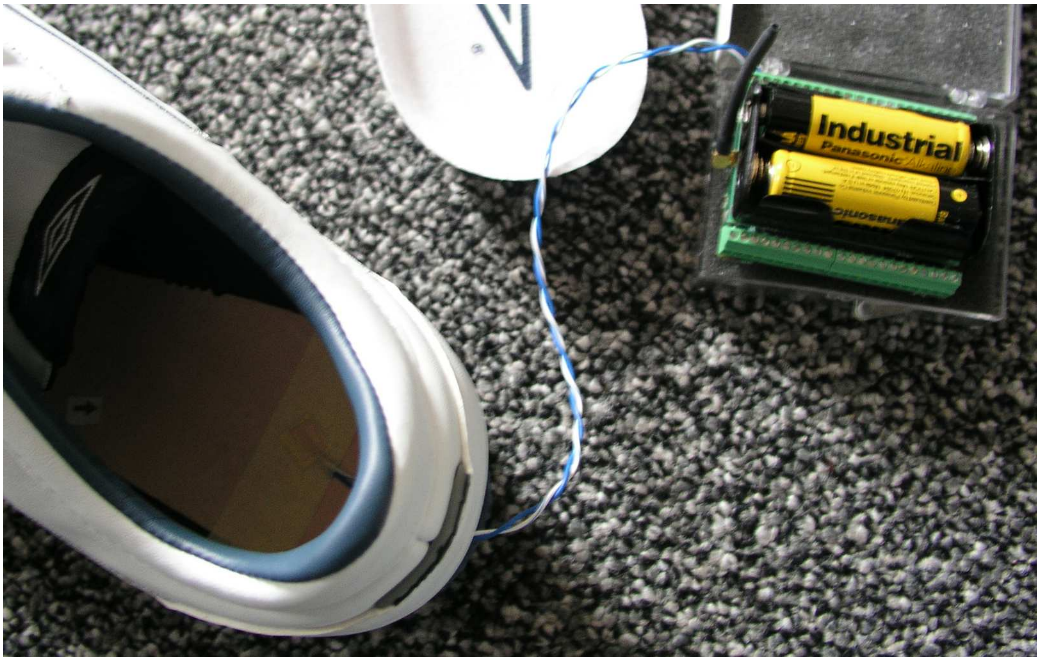
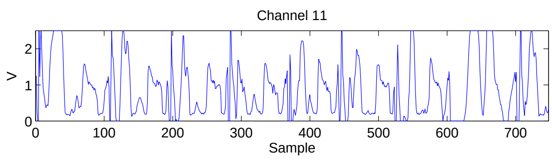
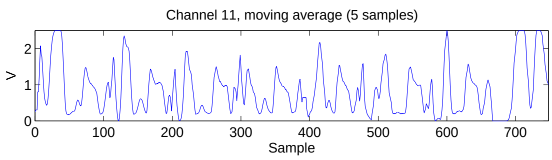


Figure 17: The setup, including the piezo film sensor attached underneath the in-sole.

Figure 18: The final setup, case strapped to the leg and activated.

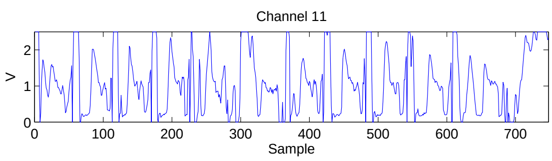


(a) In-shoe pressure measurement, walking.

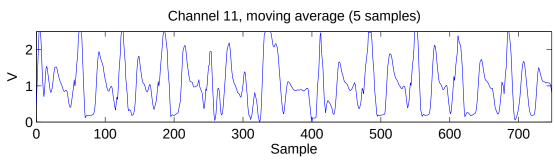


(b) Moving average using 5 samples.

Figure 19: Clear spikes are identifiable when the foot hits the ground.



(a) In-shoe pressure measurement, running.



(b) Moving average using 5 samples.

Figure 20: Clear spikes are identifiable when the foot hits the ground.

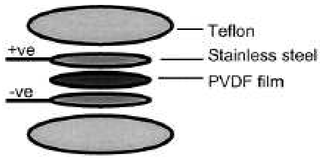


Figure 21: A piezoelectric sensor [7].

5.3 Discussion

Though the experiments were limited by the problems of crosstalk, it was useful to observe the behavior of the piezo film sensors, the ADC and the use of MICAz nodes in this context. The in-shoe pressure measurements form a good basis for further experiments though the use of additional hardware or a different ADC will be needed to avoid the problems of crosstalk.

6 Future work

With the experiments performed there are clear ways to improve the current design. While looking at the design of the Freescale 13192-SARD sensor node, it is noted that this employs a multiplexor to avoid crosstalk when using the on-board ADC. This design could be a beneficial arrangement if the time between selecting a given sensor does not incur a large overhead on sampling it for measurements.

As mentioned in Section 3, the temperature of the environment in which the piezo sensors are employed can influence the performance of the piezo sensors. Using an integrated temperature sensor as is available on e.g. the MDA300CA data acquisition board, this could be used to allow for more precise pressure measurements in the future.

Equipment was not available to perform calibrations using a pressure apparatus which allows for applying pressure with a specific force to the piezo sensors. Using this calibration, the performance of the piezo film sensor for in-shoe pressure measurement can be determined, especially with regard to Equation 2.

The sensor as it was deployed is susceptible to friction and electrical disturbances. A future design could sandwich the piezo film between layers of stainless steel and teflon, as described in [7] and illustrated in Figure 21.

Another possible setup is described in [6]:

> Double-sided circuit boards (PCB) [are] used to provide, first, electrodes and, therefore, electrical connection to the surface (Z axis) of the film and second, sufficient stiffness as bending of the film will generate electric charges and finally to provide adequate electrical shielding.

This setup is nonintrusive enough to allow for undisturbed use by the athlete, especially if directly integrated in the thickness of the sole.

7 Conclusion

Extensive experiments have been performed using the piezo film sensor, the MICAz nodes and the MDA300CA data acquisition board in the context of in-shoe pressure measurement. It has been determined that the setup described in this paper is not usable for multiple sensors, due to extensive crosstalk. A future design must take this into account.

A different platform than the MICAz/MDA300CA could be a solution, otherwise additional hardware must be used to avoid crosstalk, potentially using a multiplexor as mentioned in Section 6.

Though no final conclusions can be made with regard to the use of piezo film sensors for in-shoe pressure measurement, the work documented in this report and the work of others show that there is a clear potential in this context.

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