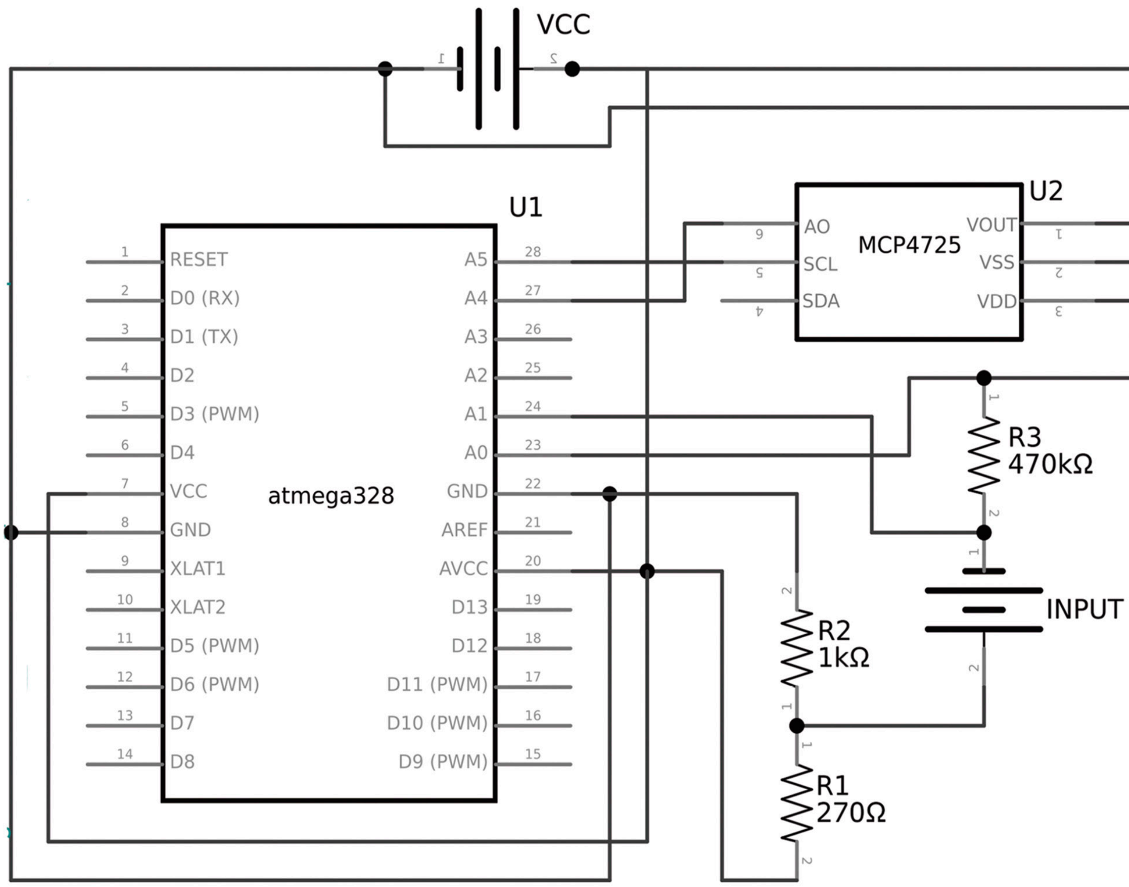

Fotografía: Juan Pablo Arenas. Diseño Gimnasio Campestre

Measuring the electric energy

of a hand-crafted piezoelectric device using a custom-made software and firmware

Measuring the Energy Produced from Piezoelectric Materials

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SUMMARY

This investigation aims to quantify the energy output of an array of piezoelectric materials by forcing a voltage into the array and measuring the current it produces, appropriating methods used for solar panels in such a way that allows an innovative way of measuring this kind of sporadic energy generation. This method was used in different situations, in which the current was measured in order to compare the different results, and provide different explanations, scenarios and final suggestions that prove useful in future builds of this kind.

Key words: piezoelectric materials, electric energy, mechanical forces, deformation, dipoles, voltage, current measurement

RESUMEN

Esta investigación propende por la cuantificación de energía eléctrica producida por una estructura de materiales piezoeléctricos, a través de la entrada de voltaje por presión del material y midiendo la corriente que produce, apropiando métodos usados en paneles solares, de tal manera que permita una forma novedosa de medir este tipo de generación esporádica de energía. Este método fue usado en diferentes situaciones, donde la corriente fue medida con el propósito de comparar los resultados y proveer diversas explicaciones, escenarios y sugerencias finales que prueben la funcionalidad en futuros proyectos de este tipo.

Palabras clave: materiales piezoeléctricos, energía eléctrica, fuerzas mecánicas, deformación, dipolos, voltaje, medición de corriente.

INTRODUCTION

Greener energies have been a priority given how fossil fuels contaminate the environment. Some alternatives have emerged, like solar, wind, and water motion energies. Those manage to generate electricity on a great scale, powering up many cities in the world. Some of those can be scaled down in order to generate enough electricity to run small appliances, but they can be troublesome to install and support on certain places, like metro stations. Piezoelectric materials are small crystals that generate electricity when pressure is applied on it. Some preliminary studies have shown some applications in which Piezoelectric materials manage to generate electricity due to people walking on them. This monograph will attempt to design, build and measure the performance of a contraption capable of generating electricity using piezoelectric materials.

THEORICAL FRAMEWORK

Piezoelectric materials were discovered in 1880 by the French physicists Jacques and Pierre Curie, but their applications are still going strong in today's society. They have multiple uses where precision and accuracy is needed. Sometimes the piezoelectric materials are used as motors, capable of moving object a couple thousands of millimeters, as they deform according to the current applied to them (Umeda et al, 1996). As their deformation is proportional to the current applied, they can be used as buzzers or speakers, producing sounds due to the vibrations they make when a sinusoidal current is applied. An interesting property about piezoelectric materials is their reversibility of this process. When a mechanical force deforms them, they produce an electrical power that can be measured for multiple applications. They are usually used this way to record musical instruments, clearly without much interference by part of external acoustics.

Contrary to the motors discussed before, piezoelectric materials can also be used as sensors due to their extreme sensitivity (that can be measured by the electrical current that they produce when exposed to said force). This phenomenon is caused due to the arrangement of the dipoles of the piezoelectric material, causing a change in the dipoles density and ultimately producing the electrical power (Umeda et al, 1996). The contrary can be said when producing the mechanical forces when applying the electrical power to the piezoelectric materials, showing the reversibility that was described by Jacques and Pierre Curie who discovered these properties in 1981. "At first, they discovered the energy potential caused by the mechanical forces applied; the next year they found experimentally about the reversibility of the process" (Seo, 1976). The efficiency of such materials has been estimated to be around 10% (Goldfarb & Jones, 1999). The energy that is released by the piezoelectric material can also be stored in energy banks (such as capacitors and batteries) and be consumed by different processes that might require it (some studies have contemplated the idea of using piezoelectric materials to power pacemakers, showing the potential of the energy harvesting) (Sodano et al, 2004).

METHODOLOGY

The methodology to be used for this project is divided in two parts, according to the objectives of this investigation. The first part consists of designing and building a circuit capable of producing electricity using the piezoelectric effect. The course of action of such circuit is the following: when a person steps on the circuit it deforms the multiple piezoelectric materials, producing electricity. After this is done, the second step consists of measuring the power output of this device. This can be done by measuring the current generated at a specific voltage (and controlling the frequency and the pressure applied to this device), and then plotting this data. This is known as an I-V curve, and is generally used for devices that generate constant energy (such as solar cells). As the energy generation of this device is sporadic, the plot will have two sub-elements: the maximum current produced and the average current produced, due to the nature of the measurements, as they are composed of multiple samples that are grouped together by the voltage in which they were measured. This means that multiple samples are taken for each point in the graph, thus making the required samples be thousands of times more than the displayed samples. The power achieved can be calculated by multiplying the voltage by the measured current.

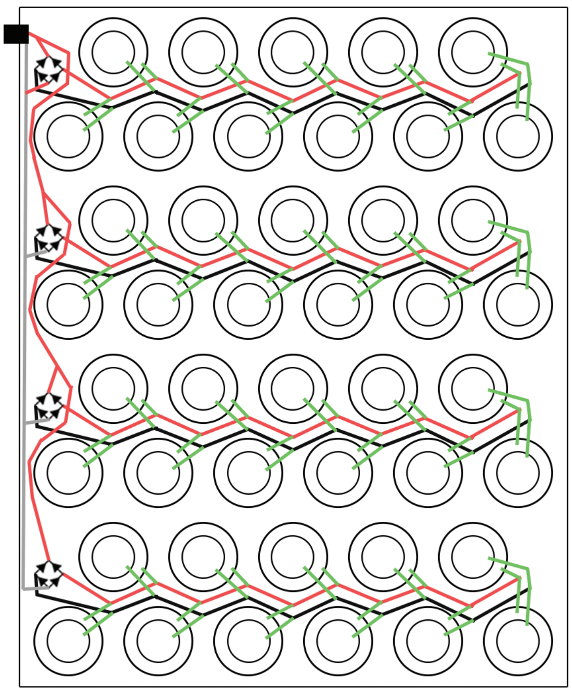

Figure 1. Schematic showing the position and circuits that collect the electricity generated by the Piezoelectric materials.

The first circuit (figure 1) shows how the forty-four piezoelectric materials used in this research were arranged in the 20cmx26cm space used. It also shows the bridge rectifiers used for each section of the prototype, converting the AC that the Piezoelectric materials produce into manageable DC. An important factor to consider is that four bridge rectifiers are used instead of only one for the entirety of the prototype, for the reason that the AC that each piezoelectric material produces can be out of sync with the one produced by the others, leading to the waves cancelling each other. For this reason, it is desirable to use more bridge rectifiers, in this case limited to four by both space and resources limitations. This bridge rectifiers are connected parallel to each other, and then interfaced to a JST-SMP connector, which is used to connect this prototype with other circuits (such as the circuit that measures the current, which is explained below). The whole framework is constructed using balsa wood, due to its low cost, and high resistance against electric current, while the piezoelectric materials were glued to the balsa wood using silicone, due to its high elasticity when solidified.

The circuit that is used to measure the performance of the prototype by measuring the

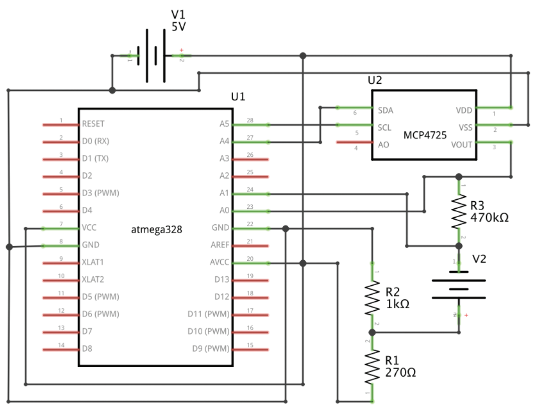

Figure 2. Schematic showing the circuit used to measure the performance of the Piezoelectric materials.

current it sources/draws is shown in figure 2. That circuit is composed of four key components: the microcontroller (in this case, an ATMEGA328P, which includes a packaged ADC), an DAC IC (MCP4725), a voltage divider, and a high resistance resistor. The way the circuit works is by changing the voltage imposed on the voltage source to be tested (the piezoelectric material prototype in this case) and measuring the voltage change in the 470kΩ resistor multiple times during the time specified by the computer host (which is set by software, and not in the firmware written in the microcontroller). An explanation of the code used is the following:

It should be noted that the software for the computer was written in Python. First it connects to the microcontroller using a Serial interface, and then enters a for loop, in which the initial value is the value of the steps (which is 20 by default), the stop value is 2^{12}-1 (which amounts to 4095), and the step value is 20. This means that a total of 204 iterations are made. Every iteration, the following happens:

```
ser.write(str(i)+"\n")
ser.write(str(timePerSample))

while(True):
   if(ser.inWaiting() != 0):
      serLine = ser.readline().rstrip()
      if(serLine == "START"):
         break
```

In which "ser" is a variable that contains an object representation of the serial connection, i is the current step in the loop, and "timePerSample" is the variable that establishes for how much time should the microcontroller collect samples. In this section, the computer sends a serial signal that tells the microcontroller the voltage at which it should collect samples, and the time that should be used for this purpose. The micro controller, which uses code written in C, answers back through the serial interface with a "START" signal, which is then followed by the data. The microcontroller does the following in order to collect the data:

```
dac.setVoltage(voltage, false);

delay(5);

long startTime = millis();

Serial.println("START");

while(millis() - startTime <= timePerSample) {
  for(int i = 0; i < REPETITIONS; i++) {
    analogRead(A0);
  }
  int firstSample = analogRead(A0);
  for(int i = 0; i < REPETITIONS; i++) {
    analogRead(A1);
  }
  int secondSample = analogRead(A1);

  Serial.println(secondSample - firstSample);
}

Serial.println("END");
```

In which "dac" is the object that interfaces the microcontroller and the DAC; "Serial" is the serial interface object of the microcontroller; "analogRead" is the function that reads the analog voltage in a certain pin; and "millis" is the function that returns the time for which the microcontroller has been running. This code first sets the voltage of the DAC. Then, in a while loop, dependent on the time set before, measures the analog voltage in the two pins, and then sends the subtraction of the two values. The reason why a buffer is not used is due to the limited memory of the microcontroller, which would limit the number of samples collected. After this loop has finished, an "END" signal is sent, so that the computer can stop listening and analyze the data. The code in the computer that gathers the data and then analyzes it is the following:

```
while(True):
  if(ser.inWaiting() != 0):
    serialNumber = ser.readline().rstrip()
    if(serialNumber == "END"):
      break
    elif(serialNumber != "START"):
sampleList.append(float(serialNumber)/1023*voltage/resistance*1000)

calculatedVoltage = resistorVoltage-(i/4095.0*voltage)
averageCurrent = sum(sampleList)/float(len(sampleList))
maxCurrent = max(sampleList)
```

This code listens for the output of the microcontroller, and stores it in a variable (called sampleList). This array contains all of the values returned by the microcontroller, up to the point where the microcontroller send the "END" signal, breaking the loop. It then uses the multiple equations that will be shown latter in order to calculate the actual values based on the data sent by the microcontroller. The data that is calculated is the voltage at which the DAC was running, the average current, and the maximum current. The maximum power is calculated using the average current and the voltage at a later point. Finally, this data is added to a bigger array, and then stored in a csv file in order to allow later graphing of these values, using another software designed for this.

This particular circuit can manage to sample at a frequency of almost 1000Hz (the limiting factor is the serial baud rate), thus allowing for thousands of samples to be collected for further analysis. With this configuration, a measurement can be made from almost -1V up to 3.6V (assuming the working voltage is 4.68V), with a 12-bit resolution in between (meaning that the minimum change in voltage that can be made is of $1.123 \cdot 10^{-3}$V). The microcontroller is programmed previous to the experiment, so the experiment parameters are set using only the computer (therefore allowing to change them dynamically between experiments if necessary)[1]. The ADC that is used for the measurements is incorporated in the microcontroller and has a 10-bit resolution across its voltage range (usually from 0V to 5V), so it can detect changes up to $4.883 \cdot 10^{-3}$V (when its rail to rail voltage is 5V). Using these conditions, the following equations can be used to calculate the current flowing from/to the source in question:

$$A = \frac{V(V_1 - V_2)}{(2^{10}-1)*R}$$

Where A is the current (in Amps); V is the voltage in which the circuit is operating (in Volts); V_1 is the unit measured before the R3 resistor (shown in figure 2) this unit is dimensionless, as it is the integer returned by the ADC, V_2 is the unit measured after the R3 resistor, and R is the resistance of the R3 resistor; (which, according to figure 2, is 470kΩ) (note the 2^{10}, which is the resolution of the ADC). Using this equation, it can be seen that the minimal measurement achievable is a mere $9.733 \cdot 10^{-9}$A, equivalent to 9.733 nA (but the accuracy when measuring voltages in the Least Significant Bit of the ADC and the noise that cannot be avoided makes this level of resolution inaccurate).

The voltage that is being forced to the source can also be calculated with the following formula:

$$V_r = \left(V * \frac{R_2}{R_2 + R_1} \right) - \frac{V * 5}{(2^{12} - 1)}$$

1. The code made for this project can be found in the following website: https://github.com/jparenas/monograph

Where V_r is the relative voltage experienced by the source (in Volts); V is the voltage of the circuit (in Volts); R_1 and R_2 are the resistance of the resistors R1 and R2 (figure 2), respectively (in Ohms); and S is the step that is sent to the DAC (this unit is dimensionless). This means that the voltage can be changed in steps of $1.143 \cdot 10^{-3}$V (assuming a working voltage of 4.68V). It is important to mention that the power measured is calculated by multiplying the voltage and the current that were computed before.

An important consideration is the high sensitivity of the circuit, as it required insulation in order to avoid noise in the measurements.

This could be attributed to many noise-inducing devices that were close to the working circuit. This was accomplished by turning all appliances near the circuit off, covering it with an insulator, supplying it with a power source that was insulated from the mains voltage, turning off the different radio modules of the host computer, and a Faraday cage that was made for the circuit, enclosing it almost completely and connecting the cage to ground to reduce the noise entering the system. The cause for such high sensitivity is the high resistance used in the circuit, as it manages to capture more noise than an equivalent circuit with a lower shunt resistance.

This was used as a way to calibrate the circuit and to see if the actions taken actually reduced the noise received by the circuit. This data was gathered by modifying the firmware of the ATMEGA328P in order to continuously send data, at a voltage of 2.08V. The first graph shows the fluctuation when all the actions previously described were made. The second graph shows the noise when the computer was connected to the power supply, showing that this affects the results.

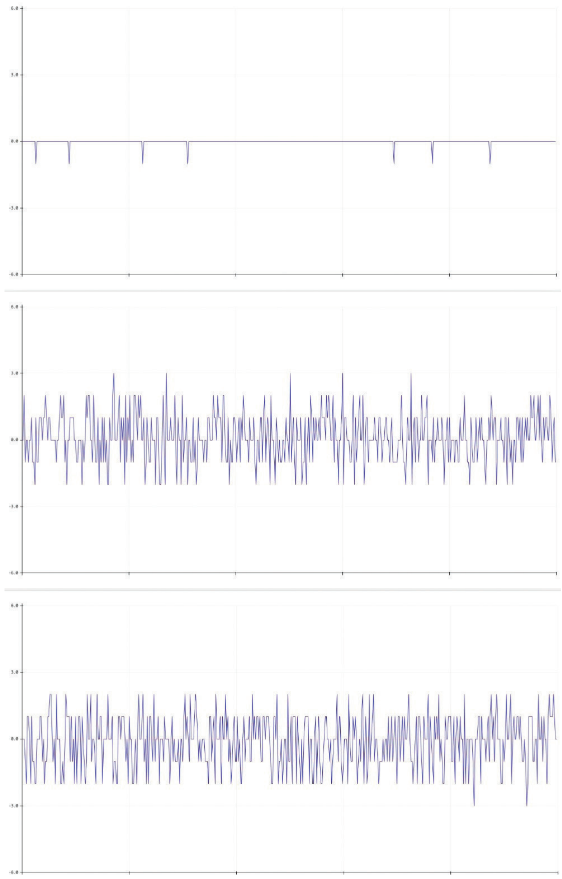

Figure 3. Graph showing the different noise received in the circuit using different parameters.

The third graph shows the noise when the aluminum foil was removed, highlighting its importance in the circuit. Overall, the noise level was successfully reduced to levels where it is negligible, thus, it can be ignored when measuring the data.

The margin of error of this circuit is calculated for each IC independently, as each one accomplishes a different function. As the resistances were previously measured, and the according parameters changed according to this, they are not taken into account for these calculations. The calculation of the margin of error for the DAC uses the various parameters given by the manufacturer (as in the DNL, the INL, the offset error and the gain error), and the final result is given by the residual sum of squares of such characteristics (when converted to volts). It is important to mention that the voltage reference used in the calculations for the margin of error is 4.68V, the same used for the experiments. The following values were used for the calculation of the margin of error:

Parameter	Value	Value (V)
INL	±2 LSB	$2.28 \cdot 10^{-3}$
DNL	±0.2 LSB	$2.28 \cdot 10^{-4}$
Offset	0.02% FSR	$9.36 \cdot 10^{-4}$
Gain	-0.1% FSR	$-4.68 \cdot 10^{-3}$

The final margin of error for the DAC (in V) would be $\pm 5.29 \cdot 10^{-3}$V. This value is higher than the minimum value that can be achieved with the DAC, therefore requiring for a lower resolution to be used (this is the reason that each sample had a 20-step difference from each other). The margin of error for the ADC is simpler to calculate, as the manufacturer lists the absolute margin of error of ±2 LSB, which, converted to volts, would be $\pm 9.14 \cdot 10^{-3}$V. Therefore, the margin of error of the ADC (in Amps, as the measurements from this IC are converted to the Amps flowing through R3) is $\pm 1.94 \cdot 10^{-8}$A. As stated before, this accuracy makes readings in the nA range fairly inaccurate. If these two values are multiplied together, the error for calculating W can be found. Thus, this error would be of $\pm 1.02 \cdot 10^{-10}$W.

RESULTS

In order to measure the current from the source, the program had to be tuned with the parameters aforementioned. The voltage of the circuit was measured with a multimeter, which amounted to 4.68V. The resistances were also measured with a multimeter, which returned the following values: R1 measured 273Ω, R2 measured 1005Ω, and R3 measured 470kΩ. A total of 204 are going to be used (therefore, a sample will be taken for every 20 steps on the DAC), with a time per sample of 4000ms. The first graph was made when the source was at rest (meaning that no pressure was being exerted on the piezoelectric material). It is important to note that in the first tries, a 60Hz noise was appearing on the results, caused by electric noise coming from the power source. This meant that the input of the circuit was not properly insulated, which is quite important as the circuit is very sensitive to changes. This was corrected using a battery with a power regulator as the source for the circuit. The results were plotted on a graph, which are shown in the Figure 4. The units used in the graph are mA and mW, which are calculated by simply multiplying the current (in Amps) by 1000.

This method was repeated for all the tests conducted, in the different floor materials and the tests where pressure was being applied in a semi-constant frequency.

DISCUSSION

There were three different tests made for the prototype: the first one involved measuring the current when the prototype was at rest and it was isolated as much as possible from the ground, by the means of reducing the surface area in contact as much as possible, and using a high-resistance material for this purpose. The second tests involved testing the prototype while it was at rest but in different types of floors, in order to determine if the type of floor in which it is located may influence the leakage current. The third one involved measuring the current on the prototype while a pressure was exerted on the device with a semi-constant frequency.

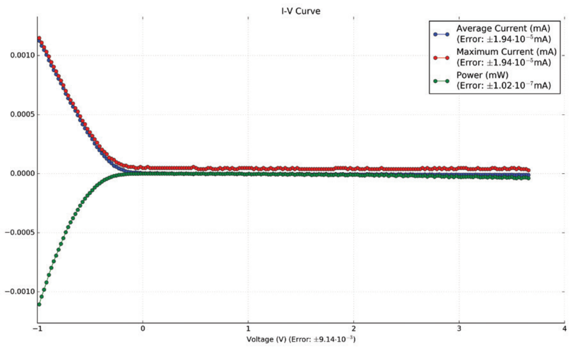

Figure 4. Graph showing the measurements gathered from the first experiment, in which the Piezoelectric materials were at rest, in a well isolated position

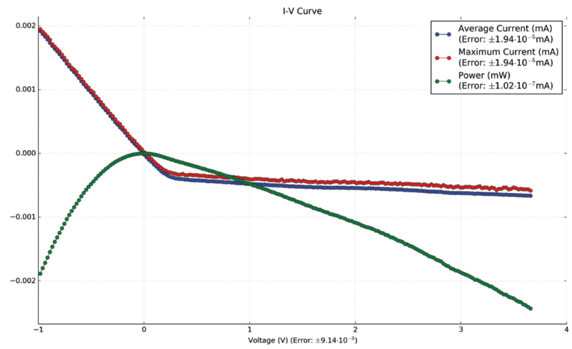

Figure 5. Graph showing the measurements gathered from the same experiment and setup as Figure 3, but the Bridge Rectifiers were composed of Schottky diodes instead of Silicon diodes.

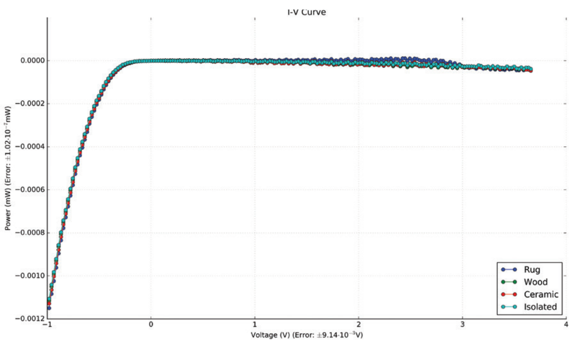

Figure 6. Graph showing the current measured on different types of ground. On order of legend: “Rug”, “Wood”, “Ceramic” floors, and “Isolated”.

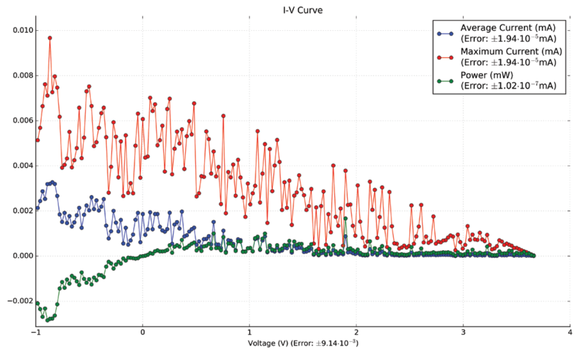

Figure 7. Graph showing the current when pressure was applied.

All the graphs that will be presented from here on will have the same scale in order to allow a direct comparison between them.

Figure 4 shows the current that flowed through the prototype while it was at rest. This current is almost zero, which means that the prototype does not waste energy from the energy collector that is connected to it. The increase in current in the negative side of the graph is due to the properties of diodes, which should not be a problem in normal operation as it would never be subjected to negative voltages (except in the case where it is plugged backwards to the energy collector, in which case it would consume the stored electricity in the collector in a resistive manner until it reaches zero volts).

Figure 4 can be compared with figure 5. The setup and the experiment in which the two graphs were made is exactly the same, with the only difference being the type of diodes used in the bridge rectifiers in the prototype. While the first graph shows the current when using silicon diodes, the second one occurs when using Schottky diodes. It should be mentioned that the second graph was made before the first graph, as the prototype first used Schottky diodes. When the second graph was analyzed, it had to be determined that a component in the prototype was provoking that leakage, and it must be corrected in order to proceed. After an extensive analysis, it was determined that the current leakage was due to the high leakage current of Schottky diodes, making them unsuitable for this application. After replacing them with Silicon diodes, the leakage was reduced

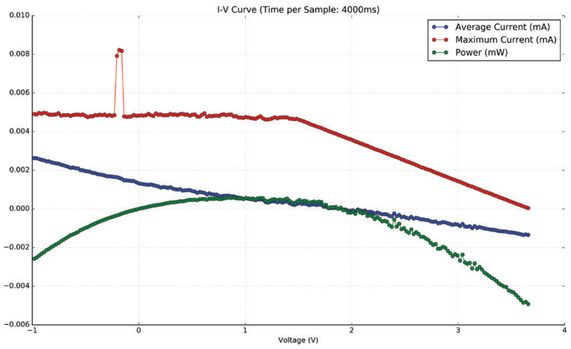

Figure 8. Graph showing the current when pressure was applied. This graph could not be adapted to the different graphs as its results were not recorded (it used an older version of the software used to measure and calculate all the samples).

by several magnitudes, showing that the correction process was correct.

Figure 6 shows the current while the prototype was resting on different ground, and while isolated. If looked closely, it can be seen that the different grounds have a little difference in terms of current consumed, seen by the small offset in the graph. Due to this, it can be concluded that the material used can be changed for materials with a higher resistance, in order to reduce leakage current to earth.

Figure 7 shows the current produced when a semi-constant pressure is applied in a semi-constant frequency. The pressure applied was of 13073.71 Pa with a frequency of 3 Hz. Overall, the results are not consistent, and the deviation from one another is caused by the method used. The highest current was achieved on 1.8974V, consisting of $8.818\cdot10^{-7}$A. The power on this point was of $1.673\cdot10^{-6}$W, and the maximum load resistance is of 2151661Ω.

Figure 8 shows the same experiment as figure 6, with the exception of the diodes used. The pressure used was of 12734.12 Pa and a frequency of 0.3 Hz. While this does not allow a direct comparison between the graphs, it shows the difference between using Schottky diodes and Silicon diodes. This experiment used the Schottky diodes, and the difference between these two is due to the lower voltage drop of the Schottky diodes, allowing them to let current more easily than Silicon diodes, and requiring a lower voltage for this to happen. As discussed earlier, this property is not enough to overcome the energy lost in the form of leakage current that flows through the diodes.

Overall, some suggestions can be made according to the multiple conclusions achieved here. Due to the numerous mistakes that happened and were corrected. First of all, the materials used to build this have to be carefully chosen, as they have an impact on the extremely current that this design handles. The material that provides the frameworks has to be both sturdy and have a really high electrical resistance, in order to avoid current leakage to earth. The type of diodes used have a significant impact on the current consumption and production. Schottky diodes allow a smoother current generation, while Silicon diodes are more sporadic. On the other hand, Silicon diodes have a lower current leakage than Schottky diodes, meaning that these would consume less current back-fed from the energy collector (such as a battery). The material which is used to bond the piezoelectric materials to the framework should also be as elastic as possible, in order to allow the piezoelectric materials to deform as much as possible. Proper channeling of wires and the bridge rectifiers should be made, in order to avoid any contact of the distribution board with the underlying circuit, diminishing the force into the piezoelectric materials. The distribution of the piezoelectric materials should be as symmetrical as possible, in order to allow the pressure applied to be distributed evenly between all the Piezoelectric materials, because if the force is not distributed evenly it can cause interference between the piezoelectric materials, cancelling out the energy produced.

Measuring the energy produced from this device proved difficult, as there were multiple challenges that had to be overcome. First of all, there was not a technique that allowed the measurement of a sporadic energy source, meaning that a new method had to be made. The method used for this is based on an I-V curve that is designed for solar panels; the problem with this method is that it is made for constant energy sources. This problem was solved by taking multiple samples and then averaging them (this samples were on the order of 1000Hz), managing to capture the sporadic production of energy and displaying it on a graph. This meant that a circuit had to be made, that could measure really low current and vary the voltage that was induced to the prototype, while reducing the noise as much as possible. The overall circuit is discussed on the methodology, but there is still room for improvement in regards to resolution, accuracy, and noise. An increase in resolution and in accuracy in purely dependent on an improvement on noise reduction. Multiple steps were used in order to reduce the noise, such as isolating the circuit from mains voltages using a battery as an energy source, turning off all radio-frequency emitting devices, and covering the circuit with aluminum connected to ground. There is still noise present, which requires more restrictive steps to be applied, which are not in the scope of this article. Both the resolution and the accuracy can be improved by using a dedicated ADC and resistors with a better rating. The resistors used in this build had a rating of 5%, meaning that their value can vary by up to 5%. This was slightly compensated by measuring their resistances and appropriating all related code to the changes.

LIMITATIONS

This research has more variables that can be measured in order to see the impact they can have in the model. These variables are: the material used to build the framework, the different types of piezoelectric crystals that can be used, different arrangements for the piezoelectric materials inside the prototype, and a more precise method to test the model under a constant pressure over a constant frequency (thus allowing to test at different pressures and frequencies). Overall, this research concludes with the same question that was proposed at first: Are piezoelectric materials suitable as an energy source? This investigation shines a negative light on that matter, but it does not conclude the topic. There are different ways how this type of models can be tested, and more effective combinations can be found that manage to generate electricity in a significant way.

ACKNOWLEDGEMENTS

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ANNOTATIONS

The code made for this project can be found in the following website: https://github.com/jparenas/monograph

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- Resumen: Máximo 10 líneas en español que destaquen los aspectos más relevantes de la investigación, seguidas de máximo 5 palabras clave en español.

- Summary: Traducción del resumen al inglés seguido de máximo 5 key words.

- Introducción: Presentación clara y concisa del problema o interrogante que se desea abordar a través del estudio, el propósito de la investigación y el estado del arte del tema mediante una corta revisión de la literatura pertinente.

- Materiales y métodos: Provee la información necesaria para reproducir el trabajo experimental, mediante la descripción de las técnicas utilizadas dentro de una secuencia que muestre de manera concreta y lógica el desarrollo de la investigación. Las fuentes y el estado de pureza de los materiales y la descripción detallada de los equipos sólo deben incluirse cuando estos sean muy específicos o novedosos. Los procedimientos descritos por otros autores se pueden obviar, pero si estos han sido modificados, se incluirán los detalles de la modificación.

- Resultados y discusión: En esta sección se presenta la información relevante derivada del trabajo experimental. Se puede presentar en tablas y figuras (cuando sea absolutamente necesario) las cuales deben ser explicadas en forma sucinta pero completa en el texto. En caso de que los resultados estén sustentados por cálculos estadísticos deberá mencionarse la procedencia de los datos y el método estadístico empleado. La discusión debe ser una interpretación de los resultados y su importancia respecto a trabajos realizados previamente por otros autores.

- Conclusiones: Se basan en los resultados obtenidos; si es posible, ofrecerán una solución al problema planteado en la introducción.

- Bibliografía: Irá al final del artículo, presentándose siempre el autor o autores en orden alfabético y ajustándose a las normas de citación APA. Deberán incluirse fuentes audiovisuales o entrevistas. Cuando sea necesario se listará la bibliografía consultada.

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- Abreviaturas: Se utilizarán las abreviaturas del Sistema Internacional.

- Ilustraciones, tablas y fotos: Deberán ser de excelente calidad y Las imágenes llevarán pie de foto y los créditos correspondientes. Las tablas llevarán título en la parte inferior, seguido de un número arábico secuencial. Las fotos podrán bajarse de Internet y su resolución será de un mínimo de 3.2 mega pixeles.

- Agradecimientos: Dirigido a todas aquellas personas o instituciones que colaboraron con el desarrollo de la investigación y/o con el artículo.

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