HIGH SCHOOL EDITION
Journal of Student Research

Volume 12 Issue 2 (2023)

Piezoelectric Energy Harvester for Mechanical Keyboards to Enable Self-Powered Computers

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ABSTRACT

A 2015 NRDC research study revealed that electronic devices consume alarming amounts of energy. To reduce the energy consumption of these devices, this project proposes a novel energy-harvesting keyboard design that allows a computer to charge as the user types on it. The keyboard generates electricity via piezoelectric materials. A novel key structure and transducer circuit were proposed to integrate the piezo materials in the keyboard and transform the electricity generated through keystrokes into a usable form. A keyboard prototype with 9 keys was used for testing. Data was collected in two rounds; the first round tested the power generated per keystroke. It was determined that the average power generated from a single key press was 0.342 µW. The second round of testing involved determining the power generated after typing at a constant rate for 5-25 seconds. The peak electrical output occurred at 25 seconds of typing, during which the total power generated was 2.38 mW. Thus, after 25 seconds of typing, 62% of a 22µF capacitor can be charged. This power output of the prototype is nearly 9 times higher than the expected power output. Given that the expected value was calculated using a higher-quality piezo than the one used in the prototype, it can be concluded that the keyboard design significantly increased the power generated. Although the needs of a computer are not fully met, this research may be applied to a hybrid charging-system utilizing both the plug-in charger and the keyboard.

Introduction

A study conducted by the Natural Resources Defense Council revealed that electronic devices, including phones, computers, tablets, etc. constitute nearly 23% of the average household's energy consumption in the state of California (Delforge, 2016). This alarming statistic was released in the midst of growing concern regarding a global energy crisis. These fears have compounded as worldwide usage of electronic devices, especially computers, skyrockets (Kotowski et al., 2021). As more people use electronic devices, the demand for energy may rise to levels that current resources are not capable of supporting. In the midst of these energy issues, energy harvesting, a subfield of electronics, is gaining traction. Energy harvesting deals with converting ambient energy in the surroundings to electricity.

Purpose

This project aims to apply energy harvesting techniques to mechanical computer keyboards and allow computers to charge via the user's typing motions. The keyboard will convert the mechanical energy from typing to electrical energy and thereby allow a fraction of the computer to be self-powered.

Methods

Piezoelectric Properties and Direct Piezoelectric Effect

To generate electricity from typing motions, this project will use piezoelectric materials, which are materials that generate electricity when a force is applied to them (Aabid, 2021). In order for materials to be considered piezoelectric, they must fulfill several criteria. First, the material's lattice structure must lack point symmetry, and secondly, the material's molecular structure must have polar bonds. Both of these specifications allow the direct piezoelectric effect to occur.

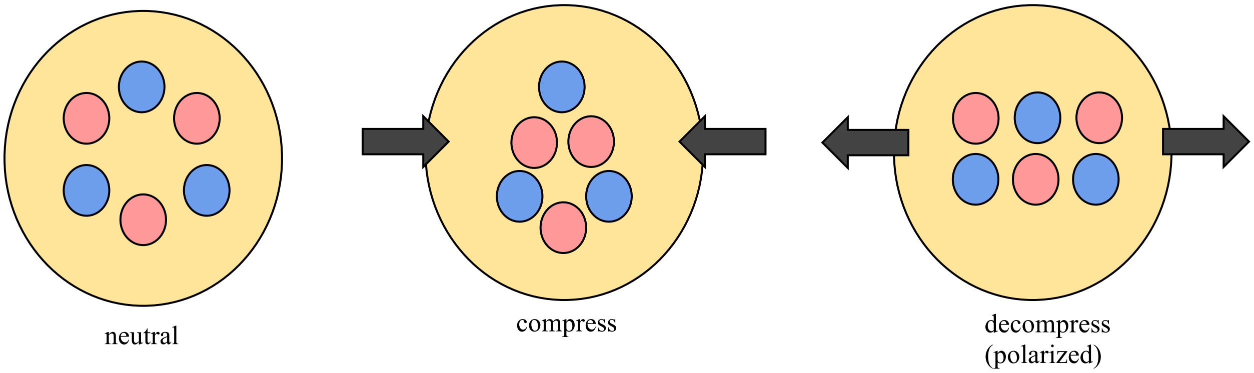

Figure 1. Diagram of the direct piezoelectric effect.

In Figure 1, the piezoelectric material lacks point symmetry and has polar bonds, signified by the differences in electronegativity. In the diagram on the far left, the piezo is at rest and neutral since the charges are evenly distributed. However, when mechanical pressure is applied, the charges drift to opposite ends of the material and polarize it. This polarization creates a small voltage across the piezo, which can be harvested according to Figure 2.

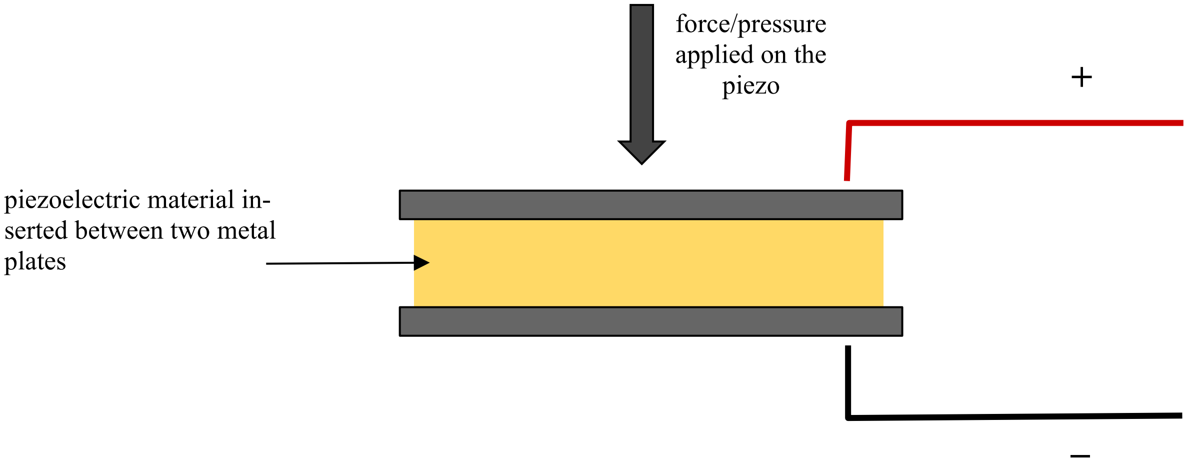

Figure 2. Electricity harvesting via the direct piezoelectric effect.

Furthermore, piezoelectric materials generally fall under two categories. They can either be crystal, which are classified as natural, or ceramic, which are classified as synthetic (Mohammadi, 2013). The most common naturally-occuring piezoelectric crystal used is quartz. Quartz fulfills the criteria for piezoelectricity mentioned above; when it is cut in a specific way, its lattice structure lacks point symmetry. Furthermore, it is composed of silicon and oxygen, elements that share polar bonds. However, quartz does not generate as much electricity as synthetic piezoceramics; therefore, it is generally only suitable for small-scale applications. On the other hand, the most commonly used synthetic piezoelectric material is PZT (lead-zirconate titanate). PZTs have a higher piezoelectric sensitivity than piezo-crystals, allowing them to produce more electricity with the same amount of mechanical pressure (American Piezo, n.d.). Furthermore, since PZT is a man-made material, is less difficult to find than quartz, and does not require as much preparation before implementing it, such as fine-slicing and compressing; additionally, PZT is much cheaper. Due to its superior electricity production capabilities as well as its affordability, PZT was deemed to be the most suitable material for this specific application in a computer keyboard.

Previous Applications of Piezoelectric Materials

To view this project in the context of similar attempts at energy-harvesting, a brief description of prior research in this field is necessary. In the past, several attempts have been made to implement piezoelectric materials in different contexts to harvest energy from the ambient mechanical vibrations. For example, piezoelectric materials have been implemented in some forms of wearable technology, such as watches (Gljuscic et al., 2019). Piezoelectric materials make these technologies more efficient, affordable, and lightweight since they allow the devices to operate without batteries. Consequently, piezoelectric wearable technology has led to breakthroughs in the biomedical field, where compact, lightweight health-monitoring sensors have been developed using piezoelectric materials (Wang et al., 2022). Evidently, although much research has been done to make smaller electronic devices more energy-efficient, there has not been sufficient research regarding the implementation of piezoelectric materials in larger devices, such as computers. This research project seeks to fill that hole in the existing technology applications by implementing piezoelectric materials in computer keyboards to make computers more self-sufficient with regards to energy.

Implementation

Theoretical Implementation

To predict the energy output of the keyboard, the theoretical power output of a piezoelectric material in a keyboard setting was calculated with the following equations (Ultrasonic Advisors, 2016). The piezoelectric material being used is PZT-5A, an affordable and commonly-used piezo. The derivations needed to predict the power output of a single key press are discussed in detail below.

Equation 1: The potential energy *U* stored by a piezoelectric material, in Watts, is equal to the product of *k*, the elastic spring constant, and *x*, the displacement of the material, in meters, divided by 2.

$$U = \frac{1}{2}k\Delta x^2$$

Equation 2: The force applied to the material, ΔF, in Newtons, is equal to the product of spring constant *k* and the displacement of the material due to the force, *L* (which can be assumed to be equal to the material's thickness in meters).

$$F = k\Delta L$$

Equation 3: The stress on the material, X (N/m^2) is equal to the elastic constant s^E (m^2/N) for a short circuit and strain σ.

$$Xs^E = \sigma$$

Equation 4: The stress X, in Newton-squared per meter, can be further described by the following equation, where F is the applied force in Newtons and A is the surface of contact in square-meters.

$$X = \frac{F}{A}$$

Equation 5: The strain σ can also be further described through the following equation, where L is equal to the displacement of the material due to the force in meters.

$$\sigma = \frac{\Delta L}{L}$$

Equation 3 may be rewritten as follows by substituting Equation 4 and Equation 5 in place of stress and strain, respectively.

$$Xs^E = \sigma$$
$$(\frac{F}{A})s^E = (\frac{\Delta L}{L})$$
$$F = \frac{A}{s^E}\frac{\Delta L}{L}$$

The equation above mimics Equation 2; therefore, we can write the spring constant k as $k = \frac{A}{s^E L}$. With this new definition for the spring constant, we can rewrite the Equation 1 as $U = \frac{1}{2}(\frac{A}{s^E L})(\Delta x^2)$. Furthermore, since the displacement x is equal to the displacement of the material due to the applied force, $U = \frac{1}{2}(\frac{A}{s^E L})(\Delta L^2)$. By multiplying by 1, we can rearrange this equation as follows:

$$U = \frac{1}{2}(\frac{A}{s^E L})(\Delta L^2)(\frac{L}{L})$$
$$U = \frac{1}{2}(\frac{A}{s^E}(\frac{\Delta L^2}{L^2})L)$$

Using Equation 5, Equation 3, and Equation 4, we can simplify and rearrange:

$$U = \frac{1}{2}(\frac{A\sigma^2}{s^E}L)$$
$$U = \frac{1}{2}(\frac{A(Xs^E)^2}{s^E}L)$$
$$U = \frac{1}{2}(\frac{A(\frac{F}{A}s^E)^2}{s^E}L)$$
$$U = \frac{F^2 s^E L}{2A}$$

Finally, to find the power P, in watts, we must divide the energy, U, by t, time, yielding Equation 6.

Equation 6: Electric power P, in Watts, is calculated by multiplying the square of the force applied to the material in square-Newtons, F^2, with the the product of elastic constant s^E (m^2/N) and the material thickness L (in meters) and dividing by 2 times the product of the material's surface area in meters, A, and time required to press the key in seconds, t.

$$P = \frac{U}{t} = \frac{F^2 s^E L}{2At}$$

Material properties for a PZT-5A piezoelectric material (Piezo.com, 2020) are given below.

Table 1. Summarized piezoelectric material properties for PZT-5A and other constants.

Radius of the piezoelectric disk	13.5 mm
s^E	15.1×10^{-12} m²/N
L	1.5 mm
Force required to press the key*	0.47 N
Time required to press the key	110 ms

*Data retrieved from (Koch, 2004).

Using the information from Table 1, the power generated through one press of the key is predicted to be:

$$P = \frac{(0.47)^2(15.1*10^{-12} \quad (1.5*10^{-3})}{2(\pi(13.5*10^{-3})^2)(110*10^{-3})} = 0.0397\ \mu\text{W}$$

Actual Implementation

Materials Used

- Schottky diodes (1n4148-type, 4 count)
- Breadboard
- Jumper wires (4 count)
- 27 mm piezoelectric disks (9 count)
- Mechanical keyboard prototype key PCB (9 count)
- Cherry MX switches (9 count)
- Cherry MX keycaps (9 count)
- 100 Ω resistor (1 count)
- 22 µF capacitor (1 count)

Design

When deriving the power generated via one key press, the piezoelectric material used for calculations was PZT-5A. However, due to worldwide shipping restrictions as a result of the COVID-19 pandemic, this prototype used a PZT piezo buzzer element, which was more readily available for commercial purchase. Furthermore, this energy-harvester is specifically designed for mechanical keyboards (such as those used for desktop computers) since mechanical keyboards have adequate space to accommodate piezoelectric materials. A possible solution to this limitation is developing a low-cost piezoelectric film that will replace the piezo-disk layer. Such piezoelectric sheets/films do exist, but they are very costly and thus not economically feasible to use in this specific application. As such, until the piezoelectric films become more cost-effective, this keyboard design can only be used in mechanical keyboards.

<u>Transducer Circuit</u>: The transducer circuit was designed in order to convert the electricity generated by the piezoelectric keyboard into a more usable form which could be used to charge a computer. Piezoelectric materials generate AC

power, which cannot be used for charging devices. Thus, the primary role of the transducer circuit was converting AC power to DC power. This is a function that many modern chargers have; the electricity from power outlets is usually AC, so most chargers have an embedded circuit that converts the AC power to DC power. Since normal transducer circuits in chargers are designed and built for very high voltages, they tend to be extremely complex. However, since piezoelectric materials produce relatively low voltages, the transducer circuit was simplified to include only a full-wave diode rectifier bridge, as can been seen in Figure 3. Furthermore, when typing, the voltage produced will not be constant and smooth since the piezoelectric material will not be pressed constantly. This is because there is a few milliseconds' gap between keystrokes, meaning that there are short intervals of time when the piezos do not experience any pressure from the user's finger. Thus, a capacitor must be inserted between the diode rectifier and the computer, as well as a resistor which is necessary for the capacitor to charge safely.

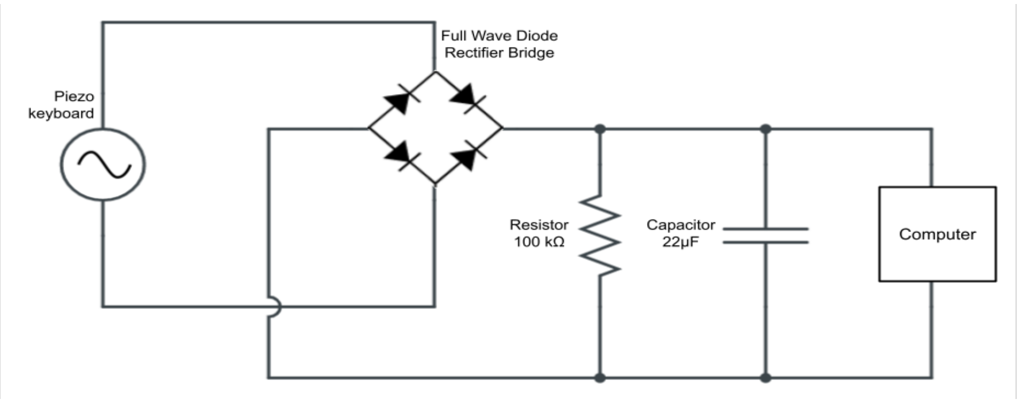

Figure 3. Transducer circuit diagram.

A full-wave diode rectifier bridge was used instead of a half-wave because a full-wave rectifier converts both half cycles of AC power to DC power (BYJU'S, n.d.), as can be seen in Figure 4. This allows the power from the piezoelectric keyboard to be converted to a smooth, DC line.

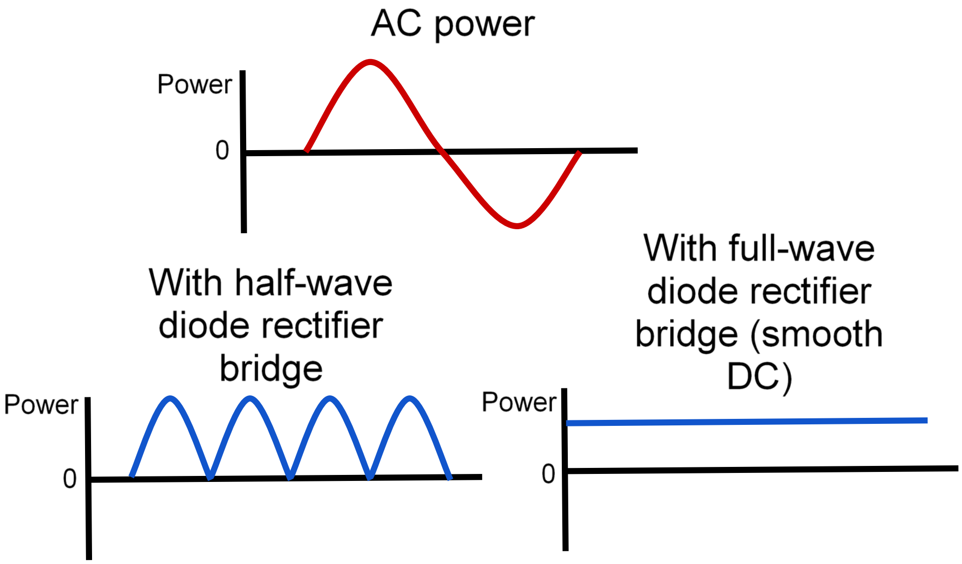

Figure 4. Diagram showing graphs of AC power through half-wave and full-wave rectifiers.

Furthermore, Schottky diodes were used to build the rectifier bridge. Schottky diodes are a type of semiconductor diode that have a very low forward voltage drop (Storr, 2022). This low forward drop allows the diodes to consume less voltage, maximizing the overall efficiency of the circuit.

Keyboard Design**:** In order to integrate the piezoelectric materials in the keyboard, a new keyboard design was proposed. First, a novel key structure was designed to seamlessly embed the materials within the keyboard while making sure that the ergonomic comfort and typing capabilities of the keyboard were retained. As seen in Figure 5, the key structure consists of stacking the computer key components, from top to bottom, in the following order: key cap, key switch, computer PCB, and piezo. By stacking the key like so, the user is able to continue to type without any physical difficulty. Furthermore, this structure ensures that the keyboard's typing functionality remains intact since the piezos do not interfere with the computer's ability to detect when the user presses a key. The key structure is repeated throughout the entire keyboard, as seen in Figure 6.

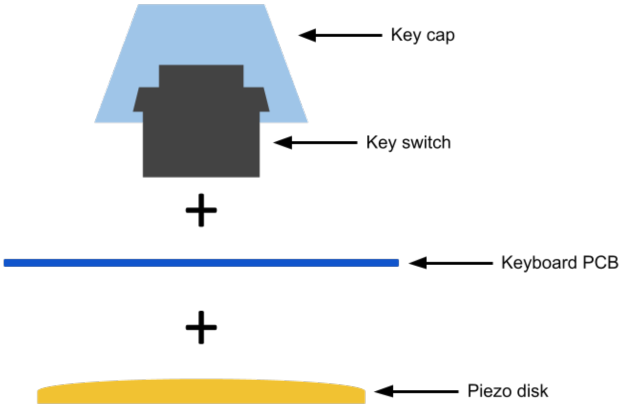

Figure 5. Diagram depicting the novel key structure.

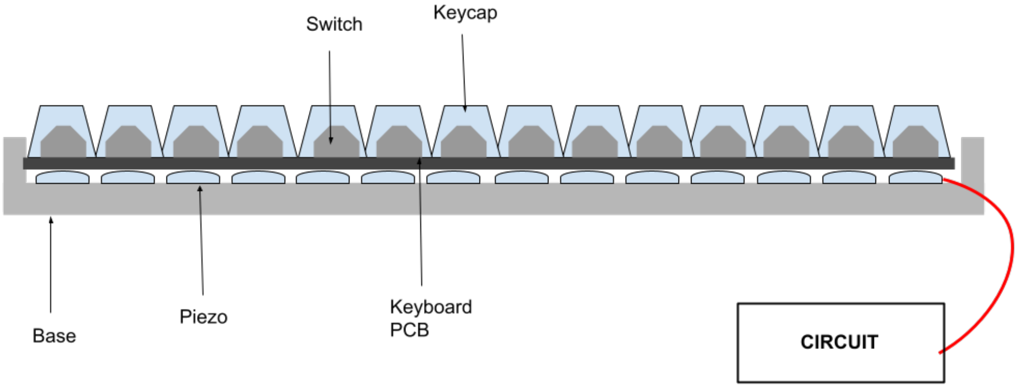

Figure 6. Diagram depicting the key structure applied to the entire keyboard.

Piezo Layer Structure: The piezos underneath the keys form a layer which can be connected in a specific way to optimize the electricity being outputted from the keyboard. To maximize the current produced, the piezos were connected in parallel, and to maximize the voltage produced, the piezos were connected in series (Hoffman, n.d.). Hence, as seen in Figure 7, the piezo layer is connected in both series and parallel in a web-like network, maximizing the electric power harvested from the keyboard.

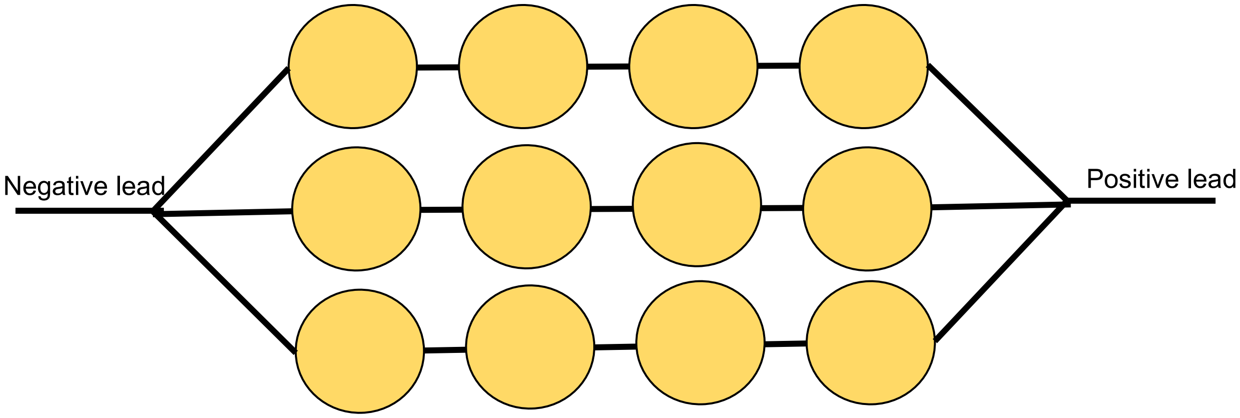

Figure 7. Structure of the piezo layer with series and parallel connections.

Results

Prototype

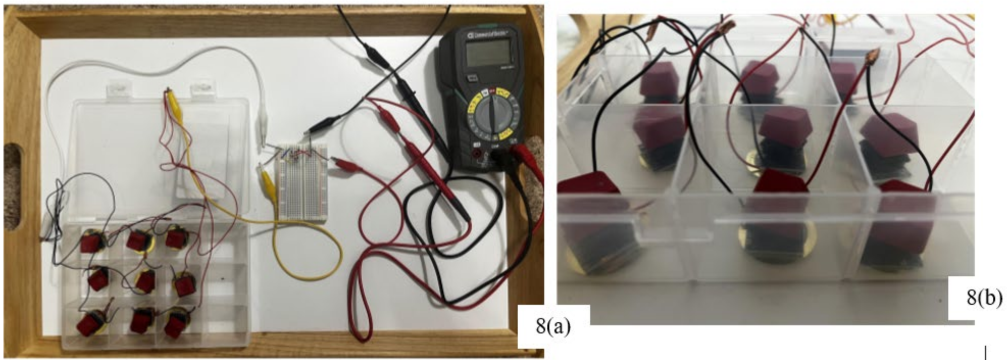

Figure 8. Image 8(a) depicts the prototype testing setup, and 8(b) is a close-up image of the prototype.

A miniature keyboard with 9 keys was built for testing purposes (Figure 8). The prototype was fabricated as per the proposed key structure and piezo layer structure, and the data was collected using a multimeter. Data was collected in two rounds. The first round measured the average voltage and current produced per keystroke, while the second round determined the total voltage and current produced after 5, 10, 15, 20, and 25 seconds of typing.

Round 1 of Data Collection

In this first round, data was collected to determine the average voltage and current produced per key press. The data was collected as follows: each key of the 9 keys in the keyboard were pressed once, and the voltage was recorded. Pressing all the 9 keys was considered one trial, with the average of the voltages produced by each individual key press being considered that single trial's voltage. Ten such trials were conducted, with the average voltage per key press being 0.2536 V. This same process of data collection was conducted for the current, with the average current produced per key press being 0.00135 mA. The greater statistical spread of the voltage values as compared to the current values (Table 2) may be caused by a number of factors, including the force being applied to the key at a different angle, a difference in the magnitude of the pressure applied, or a difference in the area of contact with the piezo, all of which affect the voltage but may not significantly influence the current.

Table 2. Data collected from Round 1, depicting the average voltage and current generated per key press.

Trial	Average Voltage per Key Press (V)	Average Total Current per Key Press (mA)
1	0.836	0.0018
2	0.182	0.0012
3	0.199	0.0018
4	0.184	0.0014
5	0.202	0.0011
6	0.229	0.0010
7	0.188	0.0012
8	0.184	0.0013
9	0.150	0.0010
10	0.182	0.0017
Average	0.2536	0.00135
Standard Deviation	0.195	0.000297

Round 2 of Data Collection

Data was collected by typing on the keyboard at a constant rate of approximately 40 words per minute for set time frames of 5, 10, 15, 20, and 25 seconds. The time frames did not exceed 25 seconds because any data collected for typing above that limit would have been unrealistic; users generally tend to type on the keyboard in small spurts of 5-25 seconds rather than for long stretches of 30+ seconds. Three trials were conducted for each time block spent typing. Table 3 depicts the average voltage and current produced.

Table 3. Data collected from Round 2, depicting the average total voltage and current after typing for 5-25 seconds.

Time spent typing	Average Total Voltage (V)	Average Total Current (mA)
5 seconds	4.22 V	0.0048 mA
10 seconds	4.37 V	0.037 mA
15 seconds	4.67 V	0.123 mA
20 seconds	7.13 V	0.097 mA
25 seconds	15.57 V	0.153 mA

Discussion

Results Summary and Analysis

Based on the data collected in the previous rounds, we can derive two main conclusions. Using Equation 7 and the data given in Table 2, The average power output from a single keystroke in Round 1 is 0.342 μW. This value is nearly 9 times higher than the expected power output from one key press (see section on "Theoretical implementation"). Given that the expected value was calculated using a higher-quality piezo than the one used in the prototype, it can be concluded that the keyboard design and piezo layer connections significantly increase the power generated; this claim is supported by the fact that the prototype generates more power than what would be expected with a much higher-output piezo despite using a low-output piezo material.

Furthermore, in Round 2, the peak electric power generated by the piezoelectric keyboard occurs at 25 seconds of constant typing, where the power generated was 2.38 mW.

Equation 7. Electric power P is equal to the product of voltage, V, in volts and current, I, in amps.

$$P = VI$$

Capacitor Charging

Table 4 displays the calculated percentage of the capacitor that is charged after each time frame, which is calculated using Equations 8, 9, and 10.

Equation 8. V_c, the voltage of the capacitor in Volts is equal to ε, electromotive force (in Volts) multiplied by 1 minus Euler's number to the power of -1 multiplied by the product of τ, the time constant (in seconds), and the multiplier k, which signifies the number of time constants passed, divided by the product of the resistance R of the capacitor (in Ohms), and the capacitance C of the capacitor in Farads (Organic Chemistry Tutor, 2017).

$$V_c = \varepsilon(1 - e^{\frac{-k\tau}{RC}})$$

Equation 9. The time constant, τ, in seconds, is the product of the resistance R of the capacitor in Ohms, and the capacitance C of the capacitor in Farads.

$$\tau = RC$$

Equation 10. The percentage of the capacitor that is charged can be calculated by dividing the voltage of the capacitor by the maximum voltage of the capacitor.

$$Percentage\ of\ capacitor\ charged = \frac{V_c}{max.voltage}$$

In Table 4, ε, the EMF of the capacitor, is equal to the voltage values from Table 3. The number of time constants passed, k, is calculated by dividing the time spent typing by the time constant, τ, which was calculated using Equation 9. These values helped compute the V_c using Equation 8. The percentage of the capacitor that was charged was calculated using Equation 10.

Constants used:

$$R = 100\ \text{k}\Omega$$
$$C = 22\ \mu\text{F}$$
$$max\ voltage = 25\ \text{Volts}$$
$$\tau = RC = (100 * 10^3)(22 * 10^{-6}) = 2.2\ \text{seconds}$$

Table 4. Capacitor charging values after each time interval of typing.

Time spent typing (seconds)	ε (Volts)	Number of time constants passed, k	V_c (Volts)	Percent of capacitor charged (%)
5	4.22	5/2.2 = 2.27	3.784	15.14%
10	4.37	10/2.2 = 4.55	4.324	17.29%
15	4.67	15/2.2 = 6.82	4.665	18.66%
20	7.13	20/2.2 = 9.09	7.129	28.52%
25	15.57	25/2.2 = 11.36	15.5698	62.28%

Sample calculations are included below:

$$V_c = \varepsilon(1 - e^{\frac{-k\tau}{RC}}) = 4.22(1 - e^{\frac{-(2.27)(2.2)}{2.2}}) = 3.785 \text{ Volts}$$

$$percentage\ of\ capacitor\ charged = \frac{V_c}{max.voltage} = \frac{3.785}{25} = 15.14\%$$

Conclusion

Based on the data collected, the current keyboard design may not be capable of independently powering a computer; this is because the average computer requires around 41W to charge while the keyboard generates a maximum of 2.38 mW. However, the electricity produced by typing may be used to charge a capacitor to 62%, which can be achieved by typing at a constant rate for 25 seconds.

This research can be applied to create a hybrid charging system that will allow the computer to charge using both the keyboard and the normal plug-in charger. Thus, the computer will be charged for the most part by the traditional charger, but a small percentage of its input will be supplied via the user's typing motions. This design will be most useful in places where computers are used often and where the computer users type frequently and for extended periods of time. An example of this could be office workplaces, where the majority of work, such as sending emails, writing reports, and programming is done on the computer. This design can also be implemented in desktop computers at schools, where students and teachers spend long periods of time typing essays, tests, and assignments. This could potentially save a significant amount of electricity if the computers are being used regularly.

Future improvements to the design include developing affordable piezoelectric films that can be used in place of the piezo elements. This will allow the piezoelectric energy harvester to be implemented not only in mechanical keyboards, but also in modern chiclet keyboards.

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