A feasibility study in energy harvesting from piezoelectric keyboards

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A Feasibility Study in Energy Harvesting from Piezoelectric Keyboards

Tom Page, Loughborough University, Loughborough, United Kingdom

ABSTRACT

The aim of the study was to investigate as to whether piezoelectric energy harvesting could be a viable contributor to a source of renewable energy for the future. Here, a keyboard usage study was conducted using a data gathering computer program called WhatPulse in which participants and their keyboards were monitored for one week. The results were used in conjunction with power output figures from work done by Wacharasindhu and Kwon (2008) who prototyped a piezoelectric keyboard and found it was capable of producing 650 μJ of energy per keystroke. The results from this study suggest piezoelectric keyboards could not be used to create self-sustaining systems for any of the devices proposed. Further uses for the stored energy have been suggested but the question to the viability of piezoelectric keyboards as a useful energy source looks discouraging. Other applications for the technology could be explored to enhance power output and utilise larger amounts of vibrational energy.

KEYWORDS

Energy, Harvesting, Piezoelectric, Keyboards, Viability, Sustainability, Experiment, Design

INTRODUCTION

Today’s living has led to the development of high-tech consumer electronics which are seemingly everywhere and in almost everything. Along with current smart devices like phones and tablets, everyday physical objects are becoming part of the wireless internet network, connected to provide feedback, remote control and intelligent management (Cisco, 2015). A smart home can now include app controlled light bulbs, robotic vacuum cleaners, smart coffee makers that synchronise to a morning alarm clock, electronic locks and active thermostats that efficiently manage the heating around a house (Crist, 2015).

Such developments have led to increased power requirements from devices and despite efforts to improve battery efficiency and performance, human energy needs will ultimately lead to the demise of fossil fuels if renewable sources are not found (Shafiee, & Topal, 2009). In addition to replacing fossil fuels and creating highly efficient systems, “self-renewable energy reservoirs” embedded in devices to continually replenish consumed power, would be highly desirable for many portable and static devices (Torres, & Rincon-Mora, 2005). Energy extraction from vibrations has long been thought of as a viable method of energy harnessing from the surrounding environment. The aim of
this paper is to investigate evidence into whether piezoelectric energy harvesting could be a viable contributor as a source of renewable energy for the future.

This work brought together current understanding of the piezoelectric effect, what it is used for and how it compares with other energy harvesting techniques. New possibilities and developments are discussed including methods of storing the harvested energy and possible design applications. Research was undertaken to assess the frequency of keyboard usage in an office environment. The results from this study were used along with current literature to produce a mathematical model to approximate the amount of power that could be harvested from daily use of a piezoelectric keyboard. An insight into the limitations of piezoelectric energy gathering and suggested areas for further research is provided.

THE NEED FOR A NEW ENERGY SOURCE

We have become reliant on the consumption of energy. In 2012 alone, it is understood humans used 37.7x10^{10}GJ (International Energy Agency, 2014) (Figure 1). Currently, 81.7% of the total energy consumption is obtained from fossil fuels, the main types being coal, oil and natural gas (Figure 2).

Our rate of consumption cannot be sustained as relying on fossil fuels are non-renewable and our reserves are rapidly declining (Höök, & Tang, 2013). Further to this, our reliance on them is negatively contributing towards global climate change due to their release of carbon dioxide when being burned (Vernon, Thompson, & Cornell, 2011). Statistics released by the International Energy Agency (IEA) demonstrate how human energy consumption continues to increase, which could become problematic in the current climate according to Shafiee and Topal (2009) who predicted all fossil fuels will run out by 2112.

Vibrational Energy Harvesting

Anton and Sodano (2007) believe one promising approach to an alternative energy source is harvesting electricity from vibrations using the piezoelectric effect. While other vibrational energy harvesting

Figure 1. World energy consumption (source: International Energy Agency, 2014)
technologies exist, such as electromagnetic induction and electrostatic generation (Torres, & Rincon-Mora, 2005), piezoelectric materials have received the most attention due to their ability to directly convert strain energy into electrical energy (Anton, & Sodano, 2007). In a study comparing different vibrational harvesting methods, piezoelectric converters were found to produce more power per unit than other technologies and have the advantage of requiring no voltage source. Contrastingly, a disadvantage was found with regards to the ability to integrate piezoelectric materials into micro systems (Roundy, Wright, & Rabaey, 2003). However, Roundy (2005) conducted a follow-up study which concluded that the integration of the best technology depends on the environmental conditions and size specifications. Further to this, Heywang, Lubitz, and Wersing (2008) contradicted Roundy et al. (2003) and concluded that piezoelectric converters are suitable for all size energy harvesting applications, especially micro scale. Conversely, they stated the maximum power capability of this technology is lower than electromagnetic and electrostatic harvesting, but this is not decisive as there are several factors that determine a technology’s success (Heywang, et al, 2008).

The advantages of piezoelectric materials make it the most promising power harvesting solution (Anton, & Sodano, 2007). Primarily, the energy required to store and use the electricity needs to be less than the harvested energy for the technology to be successful (ibid). Heywang, et al. (2008) claim this alone would not be enough for the technology to boom as a “factor of three advantages” is usually required for a new technology to overhaul alternative solutions (Heywang, et al. 2008;).

**Piezoelectricity**

The piezoelectric effect, discovered by the Curie brothers in 1880, exists in materials that generate a voltage with the application of pressure and conversely change shape when an electric charge is applied (Shields, 1966). Since their discovery, piezoelectric materials have been used for a wide variety of applications such as sonar, gramophones, watches and spark lighters (Taylor, Gagnepain, Meeker, Nakamura & Shuvalov, 1985). According to Erturk & Inman, (2011), however, only in the

Figure 2. Energy supply by fuel type (source: International Energy Agency, 2014)
last 10 years has piezoelectricity been fully recognised for its energy harvesting capabilities (Erturk & Inman, 2011). Kim, Kim & Kim (2011) believe this is because of the need for limitless power to enable the advancement of microelectronic, portable and wireless devices. Erturk and Inman (2011) explain this has led to an “explosion of academic research and new products” to enable running of low powered electronics.

In order to exploit the potential of piezoelectric materials and for it to enter the market as a viable source of clean energy, applications must be found where vibrations are frequent and low powered electronics can easily be connected. This view is shared by Anton and Sodano (2007) who believe power harvesting is vital for creating self-powered systems. Furthermore, with ever tightening power requirements to cut down on carbon dioxide emissions, the introduction of such a clean power harvesting technology would be welcomed (Heywang, et al. 2008). The implementation of self-powered systems into everyday consumer products could supply the advantages discussed by (Heywang et al. 2008) to become a viable renewable power source.

Energy Harvesting from Everyday Movement

One application of using piezoelectric materials for energy harvesting exploits human powered movement as explained by Anton and Sodano (2007). Capturing everyday movement that would otherwise be wasted is a topic similarly discussed by Beker, Muhtaroglu and Külah (2012) who applied the theory to a computer keyboard. This study agrees with earlier discussions that piezoelectric mechanisms hold advantageous characteristics in respect to high power density and ease of application. Beker et al (2012) explain electromagnetic transduction generates low voltage levels and electrostatic transduction requires initial charging of the device. The proposed system uses an array of dome switches and air channels to connect all keys to a central switch that moves up and down with keystrokes. Figure 3 shows the dome switch structure and Figure 4 shows how the switches are connected. The individual dome switches push air through the air channels which moves the main dome switch up and down.

A piezoelectric energy harvester cantilever beam is then placed above the main dome switch which generates a current when keys are pressed (Figure 5). The design is able to be implemented into a standard keyboard with the aim of keeping the cost to a minimum. The keyboard’s lifecycle and manufacture would need to be taken into account for it to be a sustainable design and feasible as a source of clean energy. The harvester is located to optimise its size and harvest the maximum energy possible within the constraints of a keyboard (Figure 5).

Figure 6 shows the experimental prototype used to test the design. A glass beam was used to simulate the operation of the main dome. A frequency in the glass of around 7.6 Hz produced from
a 1.8 MΩ load that generates 16.95 μW of power. The authors have considered sustainability when proposing the concept design by treating the volume of a standard keyboard as a limitation for the artefact’s footprint (ibid).

An experiment by Wacharasindhu and Kwon (2008) provides further evidence of a successful piezoelectric keyboard capable of harvesting 650 μJ per keystroke with 40.8 μW of power output from a skilled typist. Unlike the array of air channels described by Beker et al (2012), Wacharasindhu
and Kwon (2008) use PZT laminated between two electrodes which is integrated onto a substrate material and placed below each key (Figure 7).

The study calculates the available power that can be harvested from a range of forces exhibited by different fingers (Table 1).

Wacharasindhu and Kwon (2008) suggest that the power output could be enhanced by using different materials, changing the thickness and creating multiple layers and connecting all the keys together, the technique already explored in a similar manner by Beker et al. (2012). Another useful suggestion from the authors is to join many keyboards together to provide a more substantial amount of power. This suggestion was made due to the observations from Wacharasindhu & Kwon (2008) of low power output for a single key. Both studies report feasible systems with calculated power outputs, taking into consideration the force applied and the distance travelled by the keys. Neither study reports in any detail further uses for the harvested energy nor how much power could be harvested over an extended length of time.

**Future Role of Piezoelectricity**

As discussed, the issue that has arisen with advances in small portable electronics and limited battery life has focused researchers towards localised energy scavenging. Piezoelectric keyboards are just one example of research being undertaken to employ energy harvesting systems into everyday products. Furthermore, Kim et al. (2011) believe that harnessing energy from the surrounding environment on a micro scale could be the alternative to the conventional battery. Anton & Sodano (2007) discuss how batteries have hardly advanced compared to other technologies, a view shared by (Torres, & Rincon-Mora, 2005). The authors also comment on the dangers of chemical batteries in landfill and the inefficiency of replacing or recharging them (Torres, & Rincon-Mora, 2005). The main producers in renewable energy generation are wind and solar which can generate KW and MW but cannot easily be built into small devices (Kim, et al. 2011). In contrast, piezoelectric power harvesting has been found to only supply mW and μW, but its characteristics align with the portable world of ultra-low power electronics (Sodano, et al, 2005).

Roundy (2005) discussed that it is about applying the right technology for the environmental conditions and size specifications. It could be argued that the deciding factor to which renewable energy sources will be successful for future global supply would be the ones that generate the most power. Relating this to Heywang et al. (2008) however, they suggest that a technology to supersede

**Figure 7. Laminated PZT Key (Source: Beker et al. 2012)**

<table>
<thead>
<tr>
<th>Finger</th>
<th>Thumb</th>
<th>Index</th>
<th>Middle</th>
<th>Ring</th>
<th>Minimus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (N)</td>
<td>16</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

*Table 1. Forces from finger in Newtons (Source: Beker, et al. 2012)*
another it must have an advantage of three factors over alternatives so generating the most power is not the only aspect to consider. Combining the views of Heywang et al. (2008) and Roundy (2005) it could be suggested that different renewable energy sources will play different roles in replacing fossil fuels in the future. For these reasons, Kim et al. (2011) have stated that current research into micro energy vibrational harvesting technologies is being focused towards self-power reservoirs for portable devices and wireless systems.

Storage Methods of Harvested Energy

Kim et al. (2011) make a valid contribution to this topic by detailing the storage capabilities and the circuitry required to harness the “sporadic trickles of energy” usually found with vibrational energy scavenging (Torres, & Rincon-Mora, 2005). As an example, Ng and Liao (2005) developed a system to extract energy from a cantilever beam lined with a piezoelectric film. Findings revealed the instantaneous output was too little for practical usage and so a storage circuit was needed. Several methods have been suggested and developed to store the energy so it can be used in larger amounts after a build-up of charge.

Kim et al. (2011) presented several case studies illustrating how mechanical vibrations are harvested and the way they store the energy (Kim, et al. 2011). Mateu and Moll (2005) used piezopolymer films for bending beam structures that could be used for shoe inserts. Through analysing the voltage produced and the excitation required, they were able to find the optimum configuration for energy capture. They could then select the appropriate storage capacitor. A more in-depth study by Sodano et al. (2005) carried out experiments using piezoelectric systems to charge capacitors and rechargeable batteries. The advantages and disadvantages have been listed in Table 2 to compare the storage mediums. Ng & Liao (2005) utilised a reservoir capacitor after the energy had been rectified with a diode. The capacitor has a threshold it will charge up to before releasing its energy but the efficiency of this circuit, a topic not discussed by Mateu and Moll (2005), was 46% (Anton, & Sodano, 2007).

A follow up in-depth study, carried out by Guan and Liao (2007) investigated the use of capacitors and rechargeable batteries to store the energy from piezoelectric systems (Guan & Liao (2007). Their research compared a supercapacitor, which has a storage capacity hundreds of times higher than a regular capacitor, with two batteries, nickel and Lithium-ion. Overall, the supercapacitor and the Lithium-ion battery were favourable with maximum efficiency levels of 95% and 92% respectively. The nickel battery reached a maximum efficiency of 65%. The supercapacitor is favoured if cycle lifetime is desirable, whereas the batteries, in particular the Lithium-Ion, is favoured if storage is essential as the supercapacitor has a high self-discharge rate. The Lithium-ion battery will only drop to 95% of the full charge after 30 days, whereas the capacitor will plummet to 65% in the same time. Furthermore, the energy densities of both batteries are much higher than the supercapacitor. Guan Liao

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacitor</strong></td>
<td>Functions well under random vibrations Can be used instantaneously.</td>
</tr>
<tr>
<td>Can set thresholds.</td>
<td>Complex charging circuit.</td>
</tr>
<tr>
<td></td>
<td>Rapid discharge of high pulses.</td>
</tr>
<tr>
<td></td>
<td>Non-constant power supply</td>
</tr>
<tr>
<td></td>
<td>Needs constant vibrations to be useful.</td>
</tr>
<tr>
<td></td>
<td>Efficiency.</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td>Simple full bridge rectifier and filter capacitor.</td>
</tr>
<tr>
<td>Can store energy for later use.</td>
<td>Cannot be used instantaneously.</td>
</tr>
<tr>
<td>Delivers a constant voltage supply.</td>
<td>Damaging waste if the product goes to landfill.</td>
</tr>
<tr>
<td>Can supply power at any time, doesn’t need vibrations at time of use.</td>
<td></td>
</tr>
</tbody>
</table>
(2007) conclude that a Lithium-ion battery could be suitable for energy storage if an application needs energy to be delivered irregularly but with a constant voltage. The supercapacitor is attractive due to its high charge and discharge efficiency but should be used where the energy is needed constantly as storage would lead to wasted energy through self-discharge.

Kim et al. (2011) concluded that it is essential to use correctly calibrated circuitry to efficiently convert mechanical vibrations into electrical power. The prototypes discussed throughout the paper all demonstrate successful configurations that have been fine-tuned to reach optimal efficiency levels. These examples support the fundamental feasibility of the piezoelectric keyboards suggested by Beker et al (2012) and Wacharasindhu and Kwon (2008). The comparison of storage mediums by Ng and Liao (2005) show promising signs for efficient energy stowing in piezoelectric systems, which could be implemented depending on the size and application requirements. Piezopolymers are suggested for real life applications due to their advantageous characteristics including ability to be deformed under stress, lightweight and resistance to shock.

**Assessing the Sustainability of Energy Harvesting Keyboards**

The main focus so far has been the ability to generate power by converting mechanical vibrations from everyday movements into electrical energy. This stored energy could then be used to power small devices and potentially eliminate the need to recharge or replace batteries. Primarily, the amount of energy harvested from the piezoelectric system needs to be more than the energy required to store and output the power for beneficial energy gathering (Anton & Sodano, 2007). However, this is only assessing the product’s end efficiency and not taking into account the entire product’s lifecycle or the ‘Triple Bottom Line’ as explained by Bhamra and Lofthouse (2007). A product such as a piezoelectric keyboard may only be labelled as sustainable if all three pillars of the ‘Triple Bottom Line’ are satisfied. The components that make up this concept are economic prosperity, environmental quality and social equality. Organisations use these pillars to assess the impact of their products on society. The economic bottom line is profit, but organisations must consider the long term economic sustainability.

Nattrass and Altomore (2001) argue the environmental bottom line is the most important pillar because human society depends on the planet’s resources. Bhamra and Lofthouse (2007) support this statement and follow up by recommending companies to consider the consumption of resources, land affected, water disturbed, damaging emissions and waste produced. How the product affects the “social, ethical and political climate” of society must also be addressed (Bhamra & Lofthouse 2007). To assess these three pillars, the product’s whole lifecycle has to be evaluated. Figure 8 shows the different stages a product goes through from sourcing materials to being thrown away. Bhamra & Lofthouse (2007) acknowledge a plethora of tools for assessing sustainability but recommend a small selection which they believe to be most relevant to designers. Table 3 lists a selection of tools that could be used for evaluating a piezoelectric keyboard at different stages of the design process. The tools suggested can be used together to “achieve a more sustainable design” (Bhamra & Lofthouse 2007).

As well as using design tools to assess the sustainability of the product, a piezoelectric keyboard would have to meet standards and directives for it to reach market. An energy harvesting keyboard would initially be distributed into developing countries and so would have to comply with the WEEE directive, making producers of electrical goods responsible for what happens at the end of its life. The key focus is on decreasing the amount of electrical equipment reaching landfill. Some tools have been suggested by Bhamra and Lofthouse (2007) which could be used in the design and development stages of a piezoelectric keyboard.

**Summary and Purpose for Study**

To contextualise amongst current research, this study is required to evaluate the application of piezoelectric materials into computer keyboards. Previous research has shown possible designs for
an energy harvesting keyboard and how much power could be harvested from a single keystroke. However, this study will expand on the current literature by looking at average keyboard usage and the amount of energy harvested in a set period of time. Further to this, applications of the stored energy will be evaluated to determine the practical usefulness of the implemented technology. This will be quantified and presented as a table of suggested electronic devices that could be powered. Suggestions on how to store and distribute the energy have been analysed and methods for considering the sustainability of the product have been recommended. This research could demonstrate the
viability of using piezoelectric energy harvesting, where future research can expand on this study and discover more robust conclusions.

**METHODOLOGY**

**Background**

In order to investigate whether piezoelectric energy harvesting may be a viable contributor of renewable energy for the future an experiment was designed. This involved the monitoring of four keyboards over the period of one week to assess keyboard usage. The aim of the study was to assess, on average, how many keystrokes are made from regular use in an office scenario. This statistical data could then be used in conjunction with Wacharasindhu and Kwon’s (2008) results from their piezoelectric keyboard prototype to calculate power output. The information was collected by installing a data gathering program onto each computer to record the number of keystrokes.

**Participant Selection**

The keyboards monitored were situated in Loughborough University. Three of the participants work in admin and IT services. The fourth candidate works on their laptop every day (Table 4). These participants were specifically chosen to be representative of a common office environment and selected with help of the IT Manager. The experiment lasted one week to cover standard office hours of five working days plus the weekend. This most accurately represents a real life scenario which a piezoelectric keyboard could be implemented into. Written informed consent was gained from all participants and a University ethic approval checklist was completed. Participants remain anonymous and all data collected has only been used for the purpose of this study.

**Limitations of this Work**

Monitoring quantitative data directly from people’s keyboards allows for very detailed results that could not be obtained using any other research method (Blackstone, 2015). However, this detail can cause a lack of breadth as results are based on a small sample of people (Silverman, 2010). In this experiment, the less artificial benefits of field research outweighed the need for a large number of participants. This experiment enables a greater understanding of computer behaviour and could uncover elements of daily keyboard routines that were not previously known.

Discrete electronic monitoring using a data gathering program does not rely on self-assessment from the user or time intensive analysis from work sampling. Homana and Armstrong (2003) evaluated these three methods of assessing computer use and found user self-assessment resulted in overestimates by a factor of 2. Furthermore, recording video footage of a user’s work station would be effective for assessing time spent at computer, but for assessing keystrokes it is time consuming. In conclusion, work sampling and user self-assessment could lead to inaccurate representations of keystrokes and electronic monitoring is the most robust and non-invasive method. The variables of this experiment are the different participants; each will work differently and have varying amounts of work to type each day. A list of advantages and threats to the validity of the study has been formulated in Table 5.

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Title</th>
<th>PC/Mac/Laptop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IT Manager</td>
<td>PC</td>
</tr>
<tr>
<td>2</td>
<td>IT Technician</td>
<td>PC</td>
</tr>
<tr>
<td>3</td>
<td>Admin</td>
<td>PC</td>
</tr>
<tr>
<td>4</td>
<td>Student</td>
<td>Laptop</td>
</tr>
</tbody>
</table>
Assumptions

It has been assumed the assessment window is a normal working week and all candidates attended work as usual each day. Sick days or annual leave could occur, however this will be apparent from the results and can be analysed accordingly. The study also assumed that the candidates do not behave differently knowing their keyboard is being monitored.

Software

WhatPulse was the software selected to measure data from keyboard usage. WhatPulse counts the number of keystrokes made and uploads the results to an online account. The service is paid for and can be installed on as many computers as desired. The data collected from individual computers was uploaded and collated on www.whatpulse.org.

Combining Results: Mathematical Model

The data captured from the keyboard usage study was used in conjunction with the results obtained from Wacharasindhu and Kwon’s (2008) study on energy harvesting keyboards. The formulas to be calculated are listed in Table 6. Uses for the power output for a single keyboard will be proposed as well as power output from an array of keyboards as suggested by Beker et al. (2012). A twenty-four hour computer lab has been selected to theoretically implement an array of keyboards. There are forty computers in the lab, situated in Loughborough Design School, which are in constant use and therefore would be an appropriate environment to install such a system. Lastly, a list of suggested uses will be presented and discussed to evaluate the usefulness and viability of piezoelectric energy harvesting in computer keyboards.

Table 5. Advantages and disadvantages to study

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages/Threats to Validity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The collection of quantitative data via this experiment can be analysed and used as evidence to answering the research question.</td>
<td>1. Data will vary depending on type of work being carried out on the computer and usage could be affected by external variables such as sick days.</td>
</tr>
<tr>
<td>2. By carrying out experiments in ‘the field’, the results are far less artificial than controlled experiments.</td>
<td>2. Large number of test data needs to be collected for accurate predictions of keyboard use. Field experiments often restrict this.</td>
</tr>
<tr>
<td>3. The integrity of the test procedure can be verified easily by keeping detailed records of the data.</td>
<td>3. Candidates might change behaviour if they know their keyboard is being monitored.</td>
</tr>
<tr>
<td>4. The software is available to record the data required.</td>
<td>4. Permission from IT Manager must be obtained.</td>
</tr>
<tr>
<td>5. Date of testing can be flexible as the experiment takes place in normal working hours and doesn’t require candidates to attend a specific event.</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Formulas for power output

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Power output from one keyboard in one day</td>
<td>Average Keystrokes per day x 650µJ</td>
</tr>
<tr>
<td>2.</td>
<td>Power output from one keyboard in a week</td>
<td>Average Keystrokes per week x 650µJ</td>
</tr>
<tr>
<td>3.</td>
<td>Power output from forty keyboards in one day</td>
<td>40 x Average Keystrokes per day x 650µJ</td>
</tr>
<tr>
<td>4.</td>
<td>Power output from forty keyboards in one week</td>
<td>40 x Average Keystrokes per week x 650µJ</td>
</tr>
</tbody>
</table>
RESULTS

Outline of Keyboard Study

The amount of energy that can currently be harvested from a piezoelectric keyboard was found by Wacharasindhu and Kwon (2008) to be 650µJ per keystroke. The following results were collected to determine average keyboard usage in an office environment. By merging the numerical data from Wacharasindhu and Kwon’s (2008) and the outcome from this study, an insight into the usefulness and viability of using piezoelectric systems for renewable energy may be offered.

The seven-day study took place between the 3rd of March, and the 10th of March 2015. WhatPulse had been installed the previous week and consent forms had been signed and returned by participants. The software was configured to only monitor keystrokes and not record specific keys for privacy reasons. The results were plotted using infogram (Figures 9-14). Figures 9 to 12 show the individual candidate results over the seven-day study. Candidates 1 and 2 completed more keystrokes towards the start of the week whereas candidates 3 and 4 peaked on the Friday. Candidate 4 was the only participant to input keystrokes during the weekend. Figure 13 displays the four candidates together for comparison and Figure 14 highlights the average per day. Monday and Friday had the highest averages at 3907 and 3925 respectively.

Numerical Data

Table 7 shows the numerical data from the study and which are then accumulated to work out the averages. The average number of keystrokes per day was 2284 and per week was 15,918. These averages were subsequently taken forward to calculate the power output.

Power Output

The theoretical power output has been calculated and displayed in Table 8.
Figure 10. Candidate 2 keyboard study

![Graph showing the number of keystrokes for candidates over different days. The graph is a line chart with days on the x-axis and number of keystrokes on the y-axis. The data points are marked with circles, indicating the number of keystrokes for each candidate on each day.]

Figure 11. Candidate 3 keyboard study

![Graph showing the number of keystrokes for candidates over different days. The graph is a line chart with days on the x-axis and number of keystrokes on the y-axis. The data points are marked with circles, indicating the number of keystrokes for each candidate on each day.]

Figure 12. Candidate 4 keyboard study

![Candidate 1 - Candidate 2 - Candidate 3 - Candidate 4]

Number of Keystrokes

Days

- Tues
- Wed
- Thur
- Fri
- Sat
- Sun
- Mon

Figure 13. Average keyboard study

![Average Keyboard Study]

Number of Keystrokes

Days

- Tues
- Wed
- Thur
- Fri
- Sat
- Sun
- Mon

Candidate 1 - Candidate 2 - Candidate 3 - Candidate 4 - Average
Figure 14. Average keyboard study

Table 7. Numerical keyboard study results

<table>
<thead>
<tr>
<th>Keyboard Study</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
<th>Mon</th>
<th>Total</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate 1</td>
<td>8716</td>
<td>5627</td>
<td>5163</td>
<td>6224</td>
<td>0</td>
<td>0</td>
<td>2360</td>
<td>28090</td>
<td></td>
</tr>
<tr>
<td>Candidate 2</td>
<td>884</td>
<td>1826</td>
<td>991</td>
<td>481</td>
<td>0</td>
<td>0</td>
<td>884</td>
<td>5066</td>
<td></td>
</tr>
<tr>
<td>Candidate 3</td>
<td>998</td>
<td>1098</td>
<td>1505</td>
<td>2194</td>
<td>0</td>
<td>0</td>
<td>506</td>
<td>6031</td>
<td></td>
</tr>
<tr>
<td>Candidate 4</td>
<td>5030</td>
<td>2339</td>
<td>1562</td>
<td>6802</td>
<td>3222</td>
<td>554</td>
<td>4974</td>
<td>24483</td>
<td></td>
</tr>
<tr>
<td>Average per Day</td>
<td>3907</td>
<td>2722.5</td>
<td>2305.3</td>
<td>3925.3</td>
<td>805.5</td>
<td>138.5</td>
<td>2181</td>
<td>2283.59</td>
<td></td>
</tr>
<tr>
<td>Average per Week</td>
<td></td>
<td>15917.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Power output results

<table>
<thead>
<tr>
<th>Study</th>
<th>Keyboard Quantity</th>
<th>Time Scale</th>
<th>Calculation</th>
<th>Power Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1</td>
<td>1 Day</td>
<td>2284 x 650µJ</td>
<td>1.5J/day</td>
</tr>
<tr>
<td>2.</td>
<td>40</td>
<td>1 Day</td>
<td>40 x 2284 x 650µJ</td>
<td>59.4J/day</td>
</tr>
<tr>
<td>3.</td>
<td>40</td>
<td>1 Week</td>
<td>40 x 15918 x 650µJ</td>
<td>413.9J/week</td>
</tr>
</tbody>
</table>
The results are calculated in Joules per day and Joules per week. These power values can then be used to determine how long a device can be run for. A range of devices along with their power requirements have been obtained and are displayed in Figure 16. The pyramid shows plausible devices and components a piezoelectric keyboard could be used to power. The equations in Figure 15 were used to calculate the time each device could be powered for. These equations were rearranged from the power equation and the units adjusted accordingly.

**Study 1: One Keyboard for One Day**

Study 1 evaluated the use of one piezoelectric keyboard for one day. Table 9 shows the results of each device suggested to be powered. A standard incandescent bulb can only be powered for 25ms after a full day of typing. Similarly, fluorescent lamps and LED bulbs could not be run for over 100ms and 300ms respectively. A mini LED could be powered for around 6 minutes and a wireless keyboard for around 2 minutes.

**Study 2: Forty Keyboards for One Day**

Study 2 evaluated the use of forty keyboards for one day. Table 10 shows the results of each device suggested to be powered. Due to the low power output and the high power consuming bulbs, the piezoelectric keyboard could still only power the LED bulb for 11.9 seconds and the incandescent

---

**Figure 15. Power energy time equations**

\[
\frac{\text{Energy (Joules per day)}}{\text{Power (Joules per second)}} = \text{time (seconds per day)}
\]

\[
\frac{\text{Energy (Joules per week)}}{\text{Power (Joules per second)}} = \text{time (seconds per week)}
\]

**Figure 16. Devices with operating power consumption**
bulb for 1 second. Low powered devices such as a standard LED could be powered for 33 minutes and a wireless keyboard for over an hour.

**Study 3: Forty Keyboards for One Week**

Study 3 evaluated the use of forty keyboards for one week. Table 11 shows the results of each device suggested to be powered. After a week’s energy harvesting, the stored power could only run the incandescent bulb for around 7 seconds. On the other end of the spectrum, the wireless keyboard could now be powered for over 9 hours and the mini LED for 28 hours 44 minutes.

**DISCUSSION**

**Primary Results**

The week’s study returned a set of results that are representative of a group of keyboards situated in an office. The graphs show that candidates 1 and 4 consistently had the highest amount of keystrokes. By studying the result graphs, it can be suggested that no-one took a sick day or annual leave although candidate 2 did make less than 500 keystrokes on the Friday. This could be down to external meetings, varied work type or unforeseen circumstances. According to WhatPulse data,
Friday was the most productive day on average and unsurprisingly Saturday and Sunday had the least amount to keystrokes input.

Overall the results were fairly consistent for individual users. However, the weekly average keystrokes across participants, ranged from 5066 to 28090, a gap of 23024. Candidates 2 and 3 reduced the average and observations could be made that the admin and IT staff at a university could have different results compared to a large corporate office. Staff at Loughborough University Design School are likely to have varied responsibilities and their jobs could involve more time away from the desk than normal administrative jobs. A suggestion for further research would be to increase the sample size to gain a more accurate set of averages for keyboard usage. Also, Roundy (2005) suggested the correct environment for the size specifications was important and so the place of the study could be altered to assess the best locations to install piezoelectric keyboards.

A suggested location for piezoelectric keyboards would be public workstations where computers are used constantly during a day. Additionally, 24-hour computer labs at universities are often occupied day and night because of students varied working routines, unlike offices bound by working hours.

### Calculated Power Outputs

The power outputs for the three cases were calculated using the equations in Figure 15. Study 1 involved one keyboard for one day and produced 1.5 Joules. This figure was based on a 16N force on each stroke producing 650µJ. A selection of devices and how long they could be powered for was displayed in Figure 16 and Table 9.

Study 2 evaluated forty keyboards connected together for one day. The total power output after 24 hours was 59.4J assuming the same parameters as Study 1. The final study assessed the same array of forty keyboards, but instead for a whole week. The average keyboard usage per week was found to be 15918 which resulted in 413.9J of energy. This figure can be validated by multiplying the power output from Study 2 by the number of days in a week.

### Practical Applications of this Study

Study 1 showed a wireless keyboard could be run in full operation mode for around 3 minutes after a day’s typing on the keyboard. This finding is based on a SIIG wireless multimedia keyboard that draws 12mW in operation, 0.04mW in standby and 0.01mW in deep sleep, triggered after 5 seconds of inactivity (Siig.com, 2015). This keyboard could be powered for 10 hours in standby and 41 hours in deep sleep mode. The keyboard could only power a mini LED for 6 minutes and a standard LED for a sixth of that time. The amount of energy produced by one keyboard has been found to be very low. The calculations are also based on the highest energy output per keystroke and has not accounted

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**Table 11. Forty keyboards one week results**

<table>
<thead>
<tr>
<th>Device/Component</th>
<th>Power Consumption</th>
<th>Time Device can be powered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hours</td>
</tr>
<tr>
<td>a. Incandescent bulb</td>
<td>60W</td>
<td>0</td>
</tr>
<tr>
<td>b. Compact fluorescent lamp</td>
<td>14W</td>
<td>0</td>
</tr>
<tr>
<td>c. Dimmable LED bulb</td>
<td>5W</td>
<td>0</td>
</tr>
<tr>
<td>d. USB memory stick</td>
<td>150mW</td>
<td>0</td>
</tr>
<tr>
<td>e. Standard LED</td>
<td>30mW</td>
<td>3</td>
</tr>
<tr>
<td>f. Wireless keyboard</td>
<td>12mW</td>
<td>9</td>
</tr>
<tr>
<td>g. Cabled USB keyboard</td>
<td>9mW</td>
<td>12</td>
</tr>
<tr>
<td>h. Mini single die LED</td>
<td>4mW</td>
<td>28</td>
</tr>
</tbody>
</table>

---
for fluctuation between different finger pressures. Due to the variables assumed for this study, the power outputs are likely to be slightly less than calculated. According to Kim et al. (2011), advances in the efficiency of piezoelectric energy harvesting could see higher power outputs achieved in the near future and this is accelerated with the eruption of research being conducted. However, this study provides evidence that the power output from one keyboard alone has limited uses.

Study 2 shows that an array of keyboards connected together for a day could power the incandescent bulb for 1 second and an LED bulb for 12 seconds. The stored energy could be used to power a wireless keyboard for 1 hour 22 minutes. After connecting forty keyboards and storing 8 hours of harvested energy, the system will still struggle to make an impact on lowering energy consumption in an office environment. Study 3 shows how storing the energy over time does start to produce some usable power, being able to run a wireless keyboard for over 9 hours and a mini LED for nearly 29 hours.

Another perhaps better suited application for the power output is to help power a USB memory stick. When in use, the memory stick draws 150mW, however a memory stick is often used in short bursts to transfer data and transport it across devices. The short bursts of power required are very much suited for the energy storage in Lithium-ion batteries discussed by Guan and Liao, where energy can be stored with relatively low self-discharge and then a constant voltage can be supplied when required. With forty keyboards connected, a memory stick could be powered for over 6 minutes each day which would help to reduce power consumption over time.

With future advances in efficiency, a piezoelectric keyboard could also be effectively used to help recharge the batteries for a wireless keyboard. The keyboard discussed in this study can sit dormant and wait for a key to be pressed before switching to operation power, for this reason it would be one of the most suitable applications for the systems presented. While in deep sleep Study 1 showed a wireless keyboard could be powered for 41 hours. The storage of energy over time can be supplied when a key is pressed and the keyboard enters operation mode. Furthermore, in operation mode more energy is being harvested and stored. This model of replenishing a battery supply can be related to the topic of self-replenishing reservoirs discussed by Anton and Sodano (2007). Eventually, this could lead to self-sustaining systems where the power harvested is equal to or greater than the average power consumption of the device. However, the results from this study suggest piezoelectric keyboards are a long way from becoming self-sustaining systems. The question to the viability of piezoelectric keyboards for future renewable energy source looks discouraging.

Although the power output from this study is relatively low, piezoelectric energy scavenging still holds some advantages over other energy harvesting technologies discussed by Anton and Sodano (2007). Piezoelectric materials can be discreetly implemented into systems such as keyboards without changing the appearance of the product. This is confirmed by Beker et al. (2012) who designed an energy harvesting keyboard based on the dimensions of a standard keyboard. No external voltage supply is needed and so the footprint for the technology is small. Also, Lithium-ion batteries now come in thin flat films so the whole system could be integrated into keyboards without any noticeable changes in geometry.

**Sustainable Energy**

As discussed by Bhamra and Lofthouse (2007) the whole lifecycle of a product must be considered for a design to be sustainable. As well as the power output from the suggested system being low, this value is only achievable after the manufacture and implementation of the piezoelectric materials and appropriate circuitry. PZT is the piezoelectric material used in all concepts discussed in this paper. It contains lead which can be harmful when disposed of and according to CTS ‘Material Safety Data Sheet’, the dust produced when manufacturing PZT may be toxic (CTS Corporation, 2015). Once the material is made and manufacturing processes have been completed, the materials are non-toxic.
Limitations and Considerations

These results have been formulated using the highest power output found in Wacharasindhu and Kwon’s (2008) study. The efficiency of kinetic energy conversion has not been taken into account and the system is not likely to produce 650 µJ each time the keys are pressed. Equally, the efficiency of energy storage discussed by Sodano and Inman has been assumed 100% which is a limitation to the study. On the other hand, big companies and governments are funding larger research projects and advances in energy storage and vibration energy harvesting are quickly increasing efficiency levels and conversion rates (Kim et al. 2011). However, the technology appears to have a long way to advance before such devices could become viable.

The major problem with piezoelectric energy harvesting is the efficiency of converting vibrational energy to electrical energy. Beker et al. (2012) calculated the energy required for a user to compress one key assuming 16N of force and 5 mm displacement was 80mJ. From a possible 80 mJ, the piezoelectric keyboard concept presented can only harvest 650 µJ in the best-case scenario. This conversion efficiency of 0.8% is a big weakness for piezoelectric energy harvesting and needs to be improved if the technology is to play a big part in replacing fossil fuels as discussed by Shafiee and Topal (2009). With a piezoelectric material beneath the surface of each key, a short study should be carried out to assess whether the keyboard would feel different to type on and if that would affect a skilled typist in their job. The cost of piezoelectric materials is currently high, however once the material is installed there should be no reason to replace it unless it is damaged under pressure.

Further Uses

One possible further use for piezoelectric keyboards is in the category of emergency lighting. Guan and Liao (2007) discuss how Lithium-ion batteries are most effectively used when power needs to be stored and a steady voltage supplied. Emergency lighting sits dormant for long periods at a time and then a sudden surge of power is required in a power cut, natural disaster or other events. Such an important back up system would currently need a non-renewable source combined with the piezoelectric system to ensure the power is available. The energy stored from vibrational energy harvesting could be too little so a backup is essential. While the harvesting efficiency stays at 0.8%, current safety regulations would limit the dependency of piezoelectricity in such an emergency.

CONCLUSION

This study has assessed the usage of keyboards in an office scenario and presented a list of devices that could be powered from the power harvested if they were lined with a piezoelectric material. The principle relies on converting kinetic energy from everyday typing motions. This application of energy harvesting capitalises on reusing wasted energy that would otherwise be lost and the review of literature showed two designs for a piezoelectric keyboard. Both designs document working prototypes and present values of power output and two methods for storing the energy in situ for later use have also been proposed. The use of batteries is favourable for short or long term storage as self-discharge rates are low. Furthermore, energy stored in batteries can be used when no mechanical vibrations are present and can deliver constant voltage. However, capacitors are favourable if instantaneous power is desirable.

A data gathering program was used to capture the number of keystrokes per keyboard and the results were uploaded to a central database. Four participants had the program installed on their work computers and were monitored for seven days. The numerical data was then used in conjunction with secondary research papers to calculate power output from a piezoelectric keyboard.

From the study, it was found that on average 2284 keys were pressed each day and 15918 keys were pressed each week. From these results, the power outputs were found to be 1.5 Joules per day for one keyboard and 59.4 Joules per day for forty keyboards connected in an array. Using these
results and researching plausible uses for the power stored, a list of devices and components was formulated along with their power consumption in full operation mode. This referenced data was used alongside the primary results from the keyboard study to calculate how long each device or component could be run for from a single day’s or week’s typing. It was recorded that one keyboard used for a normal working day could power a wireless keyboard at 12mW for 2 minutes 50 seconds. It was also observed that an incandescent bulb running at 60W could only be run for 250ms. These results show that a piezoelectric keyboard on its own is not a viable source of energy as the cost of installing and manufacturing such a keyboard would greatly outweigh the useful power output.

The second study calculated the power output from forty keyboards joined together and it was found that the wireless keyboard could be powered for 4 hours and 7 minutes. Despite the number of keyboards, the incandescent bulb can still only be powered for 1 second and so it is not a sensible use. Instead, the focus should remain on small low powered electronics like the mini LED which could be powered for 4 hours. This could be related to the standby light on a PC monitor or the lights across the top of a keyboard. Finally, a USB memory stick running off 150mW could be powered for just over 6 minutes which could reduce the power consumption in short bursts. Well-thought-out applications for the power output are required for the technology to be considered as an investable product. The applications with the most potential are the ones that require short bursts of electricity such as powering a memory stick.

The final study was created to present power output from forty keyboards over a week’s worth of typing. This array of keyboards, like Study 2, are all connected and store power in a single battery that can be used to deliver constant power as required. It was found that the wireless keyboard could now be powered for over 9 hours and the mini LED for nearly 29 hours. Further uses for the stored energy include replenishment of battery supplies in the wireless keyboard. The motion of typing would reuse the wasted energy and recharge the batteries inside the keyboard. This could extend the time between recharges but with current efficiency values of 0.08%, the time gained between each charge would be minimal. Emergency lighting could be constantly recharged by the piezoelectric keyboards within an office, and then the battery can deliver all its power when required.

**Suggestion for Future Work**

A suggestion to implement the technology into 24-hour computer labs has been made to increase power output but worryingly, the amount of energy captured for keystrokes just seems to be too small to be a viable source of renewable energy for the future. The harvesting of energy from human movement is a developing technology that could one day be implemented into a large number of devices and products that humans interact with. If the efficiency could be improved, progress could be made to replace fossil fuels with renewable sources. However, the current efficiencies of piezoelectric conversion are extremely low and after manufacturing, implementing and distributing keyboards the concept becomes economically unviable. Other applications for the technology should be explored to enhance power output and utilise larger amounts of vibrational energy.
REFERENCES


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Tom’s background is in electro-optics development and production and worked for Ferranti Defence Systems Ltd. in Edinburgh. In 1990, he took up a two-year fixed-term research assistantship at the Engineering Design Research Centre in Glasgow. Upon completion of this role, he taught Computer-Aided Engineering at the University of Hertfordshire in Hatfield. Since moving to Loughborough University in 2003, Tom has taught electronic product design, interaction design, design and manufacturing technology and physical computing. His research interests are in engineering design, value management, technology education and electronic product design. Tom’s work has been widely published in the form of journal papers, book contributions, refereed proceedings, refereed conference papers and technical papers. He has supervised research students, examined PhDs and MPhils and has acted on the reviewing panel of a number of key journals and conferences.