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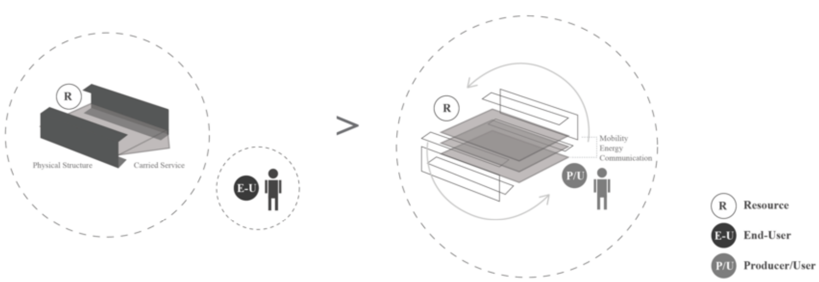
End-User no longer

Rethinking the design of distributed infrastructures considering users participation through piezoelectric technology

Elena Vanz[a], Justyna Karakiewicz[a] and Amnon Holland[b]
[a] *University of Melbourne, Australia*
[b] *Steensen Varming, Sydney, Australia*

Abstract. Infrastructure is a physical device that delivers a service needed to an end-user (consumer). Thus, it is in its identity to be formed by two distinct layers: the physical structure and the carried service. Today transition to decentralized and distributed infrastructures models focuses on redesigning the way of electricity infrastructures operate considering both a local production of the service from renewable resources and technology, and a more proactive role of the end-user.[1] Digital information and communication technology development have increasingly impacted the complexity in which electricity infrastructures operate spatially and temporally through scales, going from local to regional, national and international linkages. However, the restriction in perceiving infrastructures as individual physical objects limits the end-user as intermediary[2] and neglects the benefit of addressing its active contribution when considering cross-connections between types of infrastructures accordingly to the carried service. Over time infrastructures design has been constrained into a linear model that focuses on optimizing efficiency by increasing capacity in which individual infrastructures types operate. Optimization in distributed infrastructures can be achieved maximizing the way the whole infrastructure performs including the user contribution in defining demand and cross-connections (end-user no longer). Recent technology development in piezoelectricity, has demonstrated that energy can be harvested from the human body and stored in form of electricity. Thus the user can act as well as producer generating electricity through piezoelectric technology used as energy harvesting sensor, and consuming it for its own service(s) such as lighting and communication devices. This model is designed, built and tested in a prototype currently in process to be further explored in a design installation proposed in the City of Melbourne. This work is part of a doctoral research in progress under an ongoing multidisciplinary collaboration involving the fields of architecture, urban design and engineering.



Keywords. End-user, distributed infrastructures, piezoelectric technology

1 International Renewable Energy Agency
2 William J. Mitchell

Introduction

The following paper discusses the first of five research cycles developed adopting an Action Research approach, structured around the integration of architecture, urban design and engineering emerging from cross-connections between electricity, transportation and communication infrastructures. This first research cycle addresses the following question: How can users become producers of their own service through the use of piezoelectric technology? Piezoelectric technology has been used as the potential trigger to rethink the contribution of the end-user within a distributed infrastructure operational mode. Thus the term "end-user" has been challenged to be redundant within a new scenario where a producer of its own service is breaking the linear design of the supply infrastructure chain. This new model is tested in a prototype exploring innovative piezoelectric technology sensors designed and developed for energy harvesting purposes, and the user interface design. It is supported by technical data collection and analysis, design and construction phases, and final findings. The prototype is currently in process to be further developed and tested in a public installation in the City of Melbourne. An overall introduction on piezoelectric technology recent experimentations as energy harvesting sensor unfolds the relevant background research documentation and the need of multidisciplinary collaborations.

1. The Role of the End-User in infrastructures

1.1. Introduction to piezoelectric technology

Piezoelectric technology generates voltage when deformed. By definition piezoelectricity is the electric polarization in a substance resulting from the application of mechanical stress. [3] Many researchers have been fascinated by piezoelectric technology mainly in the field of engineering and product design considering a variety of applications.[4] All piezoelectric devices for applications in the electronics industry require two phases of design: operational principle and optimal operation, and operation device stability against environmental effects, such as temperature changes.[5] There are over two hundred piezoelectric materials that could be used for energy harvesting energy, with the appropriate ones being selected for each application.[6] With the beginning of the 21ts century piezoelectric technology has developed rapidly opening opportunities for macro scale investigations.[7] During the last decade academic research has focused on the development of piezoelectricity technology for energy harvesting, potentially be used for lighting and low-powered consuming electronics. Moreover financial investment in research into energy harvesting has expanded dramatically. It is projected that the energy harvesting market will be worth $4.4 Billion by the end of the decade.[8]

3 Oxford dictionary
4 Raghu Das
5 Jiashi Yang, Editor
6 Raghu Das
7 Harry Zervos
8 Raghu Das

1.2. The beginning of users participation

Until now, piezoelectric technology has gained public attention mainly through novel applications in indoor flooring design such as the Club Watts in Rotterdam, Netherlands, 2008. The aim of this installation is generate electricity from people dancing and using it for lighting the club. The floor exists of a modular system, with components of 65(w) x 65(l) x 30(h) cm, producing up to 25 Watts per module.[9]In this example piezoelectric technology begins to be used a trigger and the end-user actively participate in the supply chain producing the service.

The Club Watt model raises multiple questions related to technical aspects (how the piezoelectric sensors performs), to the design of the system integrating the technology (how the piezoelectric sensors are integrated within the tiles in the dance floor) and the aim of this system related to the amount of the electricity production based on the needed service (lights in the dance room: what type of lights, how many and for how long). The unrealistic expectations in this scenario strictly depend on the "type" of users demand, which is spatially translated considering the function of the room (clubs consume a high amount of electricity). In fact installing the proposed system within an enclosed functional specialized environment not only is limiting in type and number of users through time (by whom, how many and how often that room has been used), but also lack in flexibility that will allow the system to be exposed to multiple scenario, such as type and amount of users and possible contribution considering interconnection between types of infrastructures. Due to the current technological limitation in terms of electric power production, the main focus in a proposed system integrating piezoelectric sensors should move away from considering one specific function (demand) leaning toward taking advantage of the electricity produced to operate interconnectivities between demands of services. If compared the Club Watt with other renewable energy models, initial decentralized solar energy systems integration within urban environments have often failed for a similar cause. In these scenarios the production of the electricity from photovoltaic panels located on a building rooftop were expected to fully support related consumption only considering the building function and neglecting patterns in both power generation (vary daily and seasonally), and type of users demand (services needed). In Club Watt the production of electricity resulted minimal compare to the consumption and now the building is closed. Although this project has become more of a public statement, it initiates users' awareness on their capability in producing a service and establishes a valuable challenge for further infrastructural models experimentations. In this paper the presented prototype aims to address both technology limitations testing new piezoelectric sensors (hybrids designed for energy harvesting purposes), and to initiate preliminary design investigations related to the integration of the prototype as infrastructure model in urban public spaces in the City of Melbourne, Australia.

9 Studio Roosegaarde, Enviu, Architect Firm Döll

2. The Piezo High Striker

2.1. Prototype development process

The development of the prototype started with a preliminary investigation on piezoelectric technology undertaken during the first half of 2012 collecting initial data and testing multiple sensors specifically developed and designed for energy harvesting purposes. The following period of the research focused on the design and construction of a tile integrating piezoelectric technology, including electronic circuit, mechanicals and tectonics, and on testing user parameters such as velocity, frequency and weight. Findings involves the testing of a new hybrid sensor only designed and manufactured at Johnson Matthey Catalysts called V2 type, as well as user-technology interface data analysis, including the user production and consumption of the service. The prototype was built in collaboration with industry partners Steensen Varming and Arup Engineering, and it has been displayed as part of *Re-Powering Sydney* Master Design Studio exhibition at Customs House, in collaboration with City of Sydney and University of Technology, Sydney.

2.2. Design concept

The Piezo High Striker is a proposed prototype that addresses the following idea: How fast can you turn the light on? Have fun and bit your partner. The aim of this prototype is to evaluate the energy users expend when on the move to augment low powered electronic devices and lights. The Piezo High Stiker is a game where two users compete in electricity generation. Piezoelectric technology is integrated into a tile and generates electricity when users jump on it. In the original proposed model, the piezoelectric elements were to be utilized to charge a storage circuit (via a capacitor) and then use this stored power to light a LED display. The resulted voltage is monitored and displayed on a bar graph and read by the user. When the bar graph reaches full capacity, the stored charge powers LED lights located next to the tile. However due to experimental complications with the piezoelectric generator output (explained below) the bar graph was powered by a plug pack, and smaller capacitor was charged, which at a certain trigger voltage switched on a LED lights. Due to the low amount of energy harvested it is premature at this stage to consider an additional storage device to allow further control of the use of the power generated (eg. 24 hours storage).

2.3. Piezoelectric technology selection and testing

This preliminary investigation helped establishing a contact with Johnson Matthey Catalysts (formerly SIEMENS AG) in order to begin technical data collection and evaluating piezoelectric products performances as energy harvesters. This German company founded in 1817 and specialist for catalysis, precious metals, fine chemicals process technology and piezoceramic products and systems. Johnson Matthey Catalysts has been chosen as has leading global market positions in all its major businesses. Out of a broader selection of piezoelectric materials two were assessed following characteristic values such as electrical, electromechanical and mechanical data, thermal behavior and thermal data.[10] The dimensional scale of the piezoelectric materials chosen considered that there is high efficiency in smaller elements. This given role is based on: the uniform deformation the higher deformation, and no flow of charge to less deformed areas onto the metalized surface and therefore avoidance of deformation of the piezoelectric ceramic at such areas.[11] In terms of stress and strain, because of an asymmetric geometry it is possible to create the piezoelectric part in that way that the ceramic is only stressed. This is the principle to achieve a long lifetime.

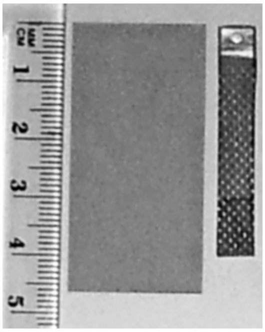


Figure 1. Piezoelectric elements tested: piezoceramic and V2 type

Two different types of piezoelectric sensors were assessed (Figure 1). One type was a single slab of piezoceramic material, which appeared much like standard sensor, or audio transducer type material in nature. The available voltage from this device could reach approximately 2 volts peak, but the stresses required to produce such voltage levels were near the breaking point of the element. The second piezoelectric generating sensor was a hybrid material only manufactured at Johnson Matthey Catalysts, Germany, called V2 Type, and more specifically designed as energy harvesting sensor. The overall element was flexible, and seems to be comprised of piezoelectric material embedded in a flexible composite. This device could produce outputs of several volts or more in response to moderate physical shock, and was highly resistant to breakage. Due to timing and logistical impediments the following prototype testes electronic circuit configuration and mechanical arrangement considering piezoelectric ceramic sensors (first type tested). However, parallel tests and analysis on power output considering V2 type establish the platform for the following prototype development.

2.4. Electrical circuit configuration to minimize diode losses and power collection efficiency

The presented circuit (Figure 2) is one of the cheaper and more efficient usages of the piezoelectric power as there is no voltage conversion needed (those circuits have inherent efficiency losses). The piezoelectric sensors output is AC in response to the

10 Johnson Matthey Catalysts, Germany
11 Johnson Matthey Catalysts, Germany

applied pressure, and a voltage doubler configuration is used to minimize diode losses per element. The size of the capacitor used determines how long it will take to reach the trigger voltage and also determines the time the lights stay on. Each piezoelectric element generally output between +- 2v AC (with associated current less than a few mA) when pressures in excess of 1kg/cm² are applied, which presents problems due to the low energy output.

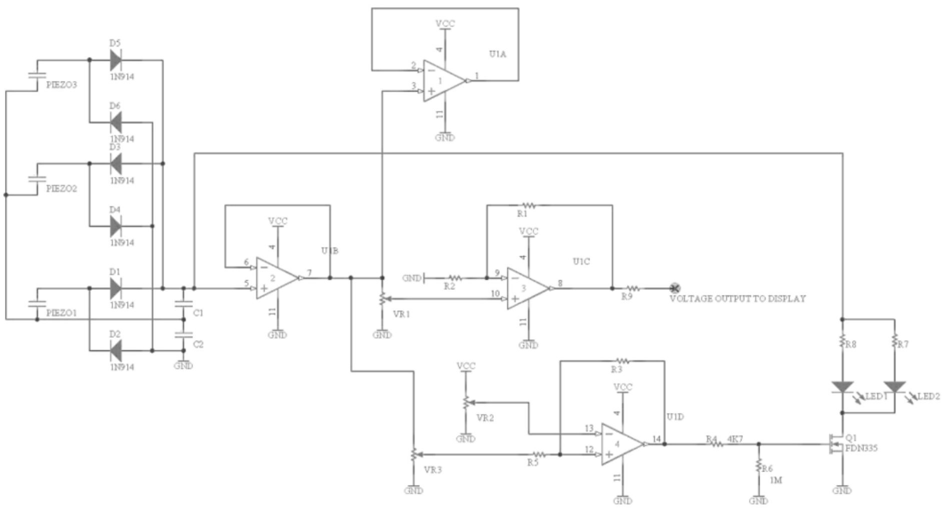


Figure 2. Electric circuit diagram for the piezoelectric tile prototype, June 2012

Due to the complex physics and mathematics involved with calculating output voltage and currents associated with deformation of the piezoelectric crystal, practical methods tend to be a much better solution to gauge output. The output voltage and current depend on many parameters including rate of change of applied pressure, non-uniformity of loading, temperature and load resistance, thus no firm parameters can be given. At short circuit conditions output current will be a few mA at maximum which depends on the volume of the sensor as well. Although this suggests the output power order of magnitude is likely to be in the mill watt range it is noted that photovoltaic systems use a similar principle with the utilization of a large amount of 'cells'. Moreover, with advances in power electronics it is envisaged that the collection efficiency of these kinds of circuits will increase. It is noted that typical collection efficiencies in the range of 30 to 60% are currently achievable with such circuits as used in this experiment. However the main complication in energy harvesting from piezoelectric sensors is due to the voltage discrepancy between elements, which could lead to back feed of power into parallel units when different pressures and rate of pressure is applied to different elements. Potential solutions to element power mismatch are a more discrete electronic collection circuits, a use of maximum power point tracking circuits, a careful disposition (design) of piezoelectric elements, a use of inline and bypassing diodes and then ultimately the mechanical configuration of these elements for even pressure distribution across the same electrically connected ‘string’.

2.5. Mechanical arrangement for uniform loadings

The second challenge with the piezoelectric energy distribution in the tile is the mechanical arrangement, so that equal pressures and rate of pressure changes are applied to the elements in order to reduce fracture or damage of the units. Since two electrical connections must be made to the element, the challenge is that when pressure is applied to the crystal, it does not crack (due to point loading i.e. from a soldered wire). Thus it is proposed that the best solution may be conductive tape since an even thickness can be applied to the front and back of the crystal for current collection, however tape resistances must be considered. To address mismatch limitation solutions are proposed considering a reduced number in parallel per “collection circuit”, a usage of rigid materials for the tile together with the optimization of the geometrical arrangement of the sensors to uniformly distribute the pressure, and an improvement in matching of sensors "electrical characteristics" from the manufacturer via automated sorting systems (eg. the one used in the solar industry for sorting and grouping photovoltaic cells with similar IV curves).

2.6. User-piezoelectric technology interface

In designing and building the structure, one footstep per tile was considered as primary parameter defining the user-technology interface design. The selection of the material considered physical characteristics such as thickness based on footstep pressure and scratch resistant, slip and waterproof resistant, costs and maintenance. A 1.3 cm acrylic stratum was used as material for covering electronics and mechanical arrangements of the system below integrated. Transparency was also a selected material property as reinforcing the participation of the user in visualizing how the whole system operates. The base of the tile was made with a solid wood slab linked to the acrylic sheet by steel L-shaped angles. Holes along the angles allowed wires to connect the tile to the bar graph and display (Figure 3).

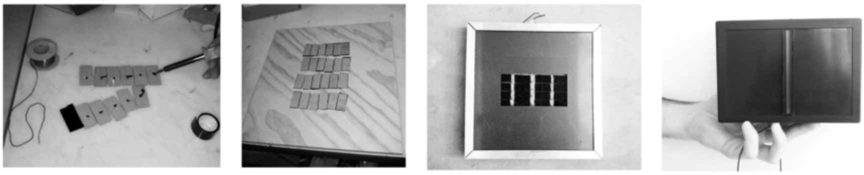


Figure 3. Tile prototype

The integration of the piezoelectric sensors within the structure aim to be electrically and geometrically optimized, thus once users step on it, point loadings generate voltage and current that the collection circuit is consequently stored. The capacitor keeps charging similar to a battery until it reaches a voltage threshold, which is enough for the electricity in the capacitor to be used to power LED lights.

3. Conclusions

Considering the initial question *how can users become producers of their own service through the use of piezoelectric technology?* this prototype validate the feasibility of it considering LED lighting output. However the implementation of piezoelectric sensors at urban scale is still questionable due to the low amount of energy harvested, calling for further experimentations especially considering additional storage devices. The presented investigation substantiated the great potential in testing new hybrid types of piezoelectric sensors such as V2 type, recently designed specifically for energy harvesting purposes. The ongoing R&D conducted on V2 and other types, such as the Bending Actuator Type, establishes continuous new opportunities for sensors testing and selection. Moreover, considering that not only volume is the parameter that can be controlled, but also placement and number of the sensors, the research further explores the possibility of increasing power generation testing the correlation between specific sensors arrangements, electronics, mechanical mounting, construction materials and pressure applied (investigated in the following research cycle). Additionally, the presented prototype has challenged the innovative concept of using sensors electrical signals for pedestrians counting. A preliminary design tested its integration in step nosing profiles considering LEDs and signal outputs as a method for lighting and communicating pedestrians' numbers and position in selected crowded urban locations in Melbourne Central Business District. When considering existing urban sites, piezoelectric sensors can be retrofitted addressing the benefits of a minimum amount of space required and compact construction, silent operation, self-sufficient and reliable (does not depend on external power sources), high resistance to humidity and none maintenance costs (15 to 20 years life-time). It is additionally envisaged that the use of piezoelectric sensors as energy harvester can be viable if the cost of the technology significantly dropped, open up opportunities for feasibility studies into the potential for mass scale utilization.

4. Following experimentations in urban design (in progress)

The next investigation currently in process represents the second of the five research cycles that aims to be completed by August 2013. This second cycle is addressing the development of the prototype discussed in this paper eventually becoming public installation to be built in the City of Melbourne. In this cycle the proposed distributed infrastructure model introduces pedestrians as users and producers of their own collective service(s) considering cross-connection between electricity, communication and transportation, and challenging viable large-scale network implementation in urban areas. As previously established, in order to use piezoelectric sensors as main energy harvesters, additional experimentations are necessary in order to maximize the electricity generation, minimizing unnecessary power losses and providing efficient storage devices. Moreover, the opportunity of combining piezoelectric sensors with other innovative technologies used as well for energy harvesting has been evaluated in order to combine complementary capabilities.

Following Melbourne City Council guidelines, the installation aim to be functional and accessible, for users affected by low vision and visual impairment as well as exciting and sustainable, challenging an innovative identity for pedestrians. The preliminary installation design aims to provide the link between technology application and user interface. It combines more permanent structures, defined through the integrated technologies on site, and temporary display designed considering tool-free assembling and selected lighting effect. Each of these parts interconnects and supports the installation operational system. Moreover, the integration of multiple technologies uncovers further experimentations and innovation in testing piezoelectric sensors as part of a broader system.

5. The relevance of multidisciplinary collaboration

Defining, researching and developing infrastructures models emphasize the importance and challenge of a multidisciplinary work involving the fields of architecture, urban design, and electric, mechanical and structural engineering. It brings together faculty and researchers from School of Design, Architecture, Building and Planning, School of Electric and Electronic Engineering, School of Infrastructure Engineering and School of Mechanical Engineering at University of Melbourne, Australia. Ongoing scheduled meetings become essential for the development of the research work considering both theoretical and pragmatic implications, although also disclose major challenges related to correlation between multiple experts and research outputs.

This work also involves local industry partners such as ARUP Engineer offering lighting design expertise, and Melbourne City Council willing to support the possible public installation. The international industry partner Johnson Matthey Catalysts (formerly SIEMENS AG), a German piezoelectric products manufacture, has been approached to provide the piezoelectric technology and more specific technical expertise. An additional collaboration with Samsung Group is in process to be established, including a fieldwork in Seoul, Korea. Samsung Group will bring the unique expertise of integrating piezoelectric technology into low powered electronic devices collaborating with local piezoelectric technology industries and testing different type of piezoelectric elements. This overall multidisciplinary cooperation is essential to fully explore potentials in designing the proposed distributed infrastructure model. It emphasizes once more the benefits of linking academic research projects and professional work focusing on the same agenda.

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