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Powering lights with piezoelectric energy harvesting floors

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Abstract: The present work introduces a new technology for converting energy from steps into electricity. It starts with a study on the mechanical energy available from steps in a busy corridor. The subsequent development efforts and devices are presented, with an iterative approach to prototyping. Methods for enhancing piezoelectric conversion efficiency have been found as part of the process, and are introduced in the present article. Capitalising on these findings, we have fabricated energy harvesting demonstrators for stairs that power embedded emergency lighting. The typical working unit comprises an energy harvesting stair nosing, a power management circuit, and an embedded LED that lights the tread in front of the user with an illuminance corresponding to emergency standards. The stair nosing generates up to 17.7 mJ of useful electrical energy per activation to provide up to 10.6 seconds of light. The corresponding energy density is 0.49 J per meter square and per step, with an 8.5 mm thick active layer.

Introduction

Harvesting energy from steps is an exciting and equally challenging scientific and technological undertaking. Several efforts have been made by the scientific community and companies, leading to energy harvesting devices with various form factors, and power outputs. Work has been carried out on two main approaches: inserting energy harvesting components into floors or shoes. Some authors proposed devices that can be attached to human limbs. In the present project, we focused on generating energy from steps with active floors, as this is a joint effort between an academic institution and a flooring coverings manufacturer.

Research into energy generation with steps lead to the development of several techniques, heel- strike energy harvesting being the most common one. In 1996 Starner proposed one of the first estimations of the mechanical power available from heel strikes [1]. It is calculated that 67 W are developed by a person walking at a pace of 2 steps per second, with the possibility of extracting 5 W with piezoelectric shoe inserts. Niu et al. estimate the useful energy available at 0.4 to 1 J/step [2]. They predict that the maximal electrical power extracted from heel strikes would be 2 W for a user walking at 2 steps/s. Shenck and Paradiso have developed energy harvesting soles based on PVDF and PZT piezoelectric materials [3]. Test results show that the PVDF sole generates approximately 1.3 mW of power for a strike frequency of 0.9 Hz, while the PZT design produced 8.4 mW. In both cases the generated power is dissipated in resistors. The authors have also tested storing the energy to power an RFID transmitter circuit embedded in the shoe.

Various other shoe or limb mounted devices have been designed, exploring different force transmission techniques. Howells investigates a mechanism with lead screw and cam that activates piezoelectric cantilevers[4], while Alghisi explores activation of piezoelectric membranes with a metal ball that is free to move in a cavity[5]. Xie designed a device that uses an amplification mechanism with sliders to generate high strain in piezoelectric bimorphs[6].

Studies on nonlinear techniques for piezoelectric energy harvesting from human motion have been proposed by Green[7] and Cao[8].

Investigations on energy harvesting floors have been conducted by actors from academia and companies. Sharpes designed a tile based on PZT cymbal transducers capable of powering wireless signal transmissions[9], while Bischur proposes using PVDF based modules[10]. Notable efforts have been conducted in developing electromagnetic energy harvesting tiles[11]. Speaking about energy harvesting stairs, a study has been proposed by Puspitarini[12]. It is focused on collecting information on the user's needs to define a sustainable stairway concept.

Our research efforts have been focused on developing an energy harvesting floor based on piezoelectric technology[13]. This choice is due to readily available materials and the thin form factor piezoelectrics allow.

Since our goal is to convert mechanical energy developed by a person walking into electrical energy, we started our research by evaluating the former. We built in parallel our first devices and evaluated the electrical energy recovered with PZT based piezoelectric materials. Once aware of the gap between the available and recovered energy, we started a process of enhancement which allowed us to increase significantly the power output and efficiency.

The technological choices during the development journey and the reasoning behind them are described in the following sections.

Results

The mechanical energy per step

Literature[14] shows that while stepping a person develops a vertical force pattern that resembles the letter M. Our own gait analysis recordings confirm this, as reflected in Figure 1. The two peaks correspond to precise moments of the gait cycle. The first peak is reached when the foot finishes landing, and is in full

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contact with the floor. It comes at the end of the gait phase also known as the heel rocker, when the foot revolves around the heel[14]. A valley follows, with the force diminishing generally to around 50% of the peak, while the other foot swings forward. The subsequent increase in force culminating with the second peak is due do the acceleration of the foot in preparation for “take-off”. The second peak is reached just before the heel starts rising. This is the end of the phase called “ankle rocker” when the dominant movement is the rotation of the leg around the ankle.

In the measurements presented in Figure 1, the average peak force is 1143 N for a subject weighing 87 kg. This is 33.9% greater than the body weight. The average local minimum in the valley is 44% of the peak. These ratios are close to data found in literature.

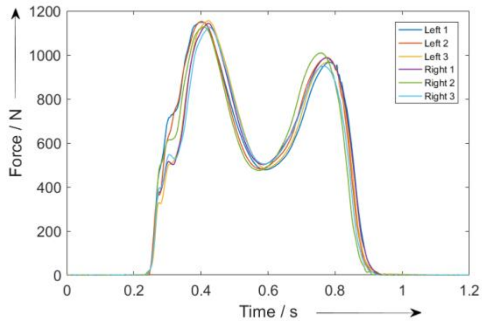

Figure 1. Forces developed when stepping. Measurements for the left and right foot of the subject are presented, as recorded with a force plate. The subject weight is 87 kg.

The peak forces while walking are generally 20 to 30% greater than the bodyweight, this being the first input into the calculation of the mechanical energy that is generated. The second input should be the displacement induced in the floor surface. While a person walks the flooring is subjected to some degree of deformation. Simple physics shows that the mechanical energy stored in an object depends on its deflection and the forces involved. The same can be applied to a portion of flooring on which a user steps:

$$E_m = \int F \cdot dz$$

with E_m – the mechanical energy, F – the vertical force exerted on the floor, and z – the average deflection under the foot.

Since precise force versus deflection measurements are not trivial, we choose to make an estimation of the energy supposing a linear increase. With this in mind, the peak mechanical energy becomes:

$$E_{max} = \frac{1}{2} \cdot F_{max} \cdot d_{max}$$

with F_{max} – peak force, and d_{max} – peak deflection.

In the case of an energy harvesting floor, the maximal deflection will be the one allowed by design. Indeed, we would want to protect the active piezoelectric elements by limiting the amount of strain they are subjected to. This allows estimating the mechanical energy that one can generate per step in a typical case:

$$E_m = \frac{1}{2} \cdot m \cdot g \cdot d_{max} = 0.47\,J$$

for a typical weight of 76.5 kg and 1 mm floor deflection.

Without surprise, the higher the force involved, the higher the mechanical energy that can be converted into electricity. Roughly half a joule of mechanical energy will be generated by an average person on a floor that allows 1 mm of deflection. This amount will increase to 1.41 J for 3 mm deflection, and to 2.35 J for 5 mm. Although this is an estimation relying on a supposition of linear variation of force with deflection, it gives a good understanding of the order of magnitude of the energy that can be generated while walking. Therefore, it is safe to say that this order of magnitude is of 1 J/step.

The contribution of the deflection to the energy is worth a more detailed analysis. According to the expression above, a floor that gives in more will store more energy than a floor that hardly deforms for the same user. In the second case the energy will be stored elsewhere: shoes, legs, joints of the user, or vibrations of the substrate, and will be dissipated through thermal effects. Therefore, in order to maximize energy generation we will have to allow for some deflection, enough to harvest the desired amount without compromising the comfort of the user or reaching the strain limits of the flooring materials. This conclusion is valid independently of the energy conversion technology employed. The latter will determine the amount of electrical energy in the output by its efficiency.

Energy in a busy corridor

The next step of the study is calculating the amount of energy that can be generated per day in a busy corridor inside a public building. This will give an idea on the upper limits of energy harvesting from steps as a solution for powering lights and building systems.

We used optical counting to monitor the number of users in a portion of a busy university corridor. A camera connected to a data processing system has been installed in a corridor with high traffic, and counted the number of users during 3 months. The complete statistics are shown in Figure 2.

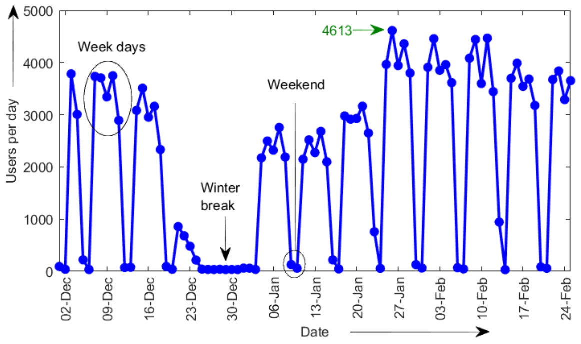

Figure 2. Traffic in a busy university corridor, as recorded by an optical counting system.

One can notice the weekly cycles, with maxima reached during working days, and low traffic during week-ends and the winter break. The maximum traffic on the portion of corridor under study is 4613 users per day. Considering that the average stride length of a person is 76 cm, an energy harvesting floor with the same length will harvest 4613 steps per day. If this flooring allowed 5 mm deflection, the users would generate 11500 J per day, or 3.2 watt-hour. Supposing a harvesting technology with 50 % mechano electrical conversion efficiency, 1.6 Wh will be stored as electrical energy for use. This would amount to 210 Wh per day with 100 m length of active flooring, or 77 kWh per year with sustained high traffic every day.

Knowing the price per kilowatt-hour of electrical energy it is easy to determine that an energy harvesting flooring will most probably not be a cost-effective solution for powering main lights or other building systems like heating or air conditioning, even in a busy corridor.

The main conclusion of this study is that energy harvesting from steps is more suitable for low power applications. One can cite building monitoring and safety: place and forget environmental sensors, intrusion detection, requiring just one alert per event, or low-level lighting. The latter, and more precisely powering emergency lighting, is our application of choice that we decided to develop further, as described in the next sections.

Design of an energy harvesting tile

We built our first step energy harvesting devices using commercially available piezoelectric membranes. Elements like the one presented in Figure 2a have been employed. They have an outer diameter of 50 mm. The first representative prototype consists of a 8x7 matrix of circular piezoelectric membranes, connected to the same output through conductive paths (Figure 3b).

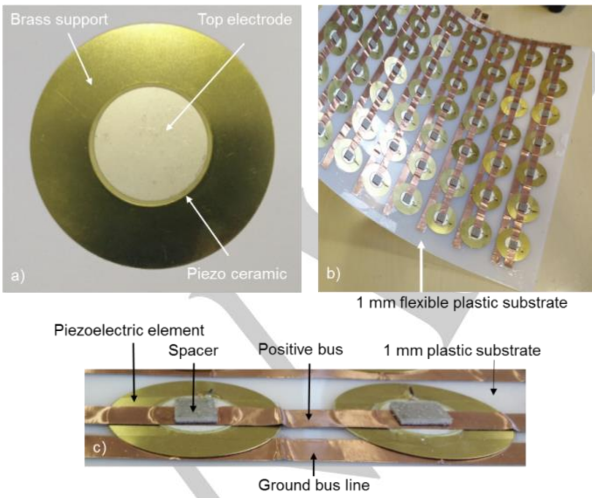

Figure 3. Structure of the energy harvesting tile active layer: a) commercially available piezoelectric element as used in the assembly; b) active matrix of 8x7 elements on a flexible substrate; c) structural detail. Spacers are used for actuation purposes. Air gaps are left below the piezoelectric membranes to allow for deflection (not shown).

Conductive tape is used to collect the charge generated by the piezoelectrics. All the elements in the matrix are connected electrically in parallel. Conductive paths below the membranes are in contact with the ground electrodes while a second set of paths run above the top electrode (Figure 3c). Each set of paths is then directed towards the common output. An air gap is left below each piezoelectric (not shown on the figure) through an incision into the substrate. It allows each piezoelectric element to deflect by 1 mm upon actuation. The surface supporting the assembly acts as a mechanical stop, to limit the deflection of the membranes. A spacer is placed at the centre of each piezoelectric element to transmit the effort coming from the foot of the user.

A rigid top plate is used to distribute the walker’s force across the piezoelectric matrix. Here we use a 0.9 mm steel sheet. To complete the assembly, the whole is covered with a slip resistant flooring layer and two LED strips are applied on the edge, to be powered by the prototype (Figure 4).

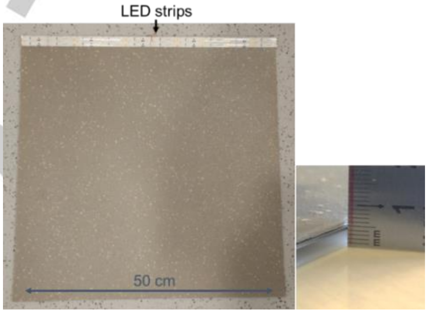

Figure 4. 50x50 cm^2 energy harvesting tile with embedded LED strips. The total thickness, including the slip resistant upper layer, is 7mm.

Performance of the energy harvesting tile

The energy harvesting tile has been tested in real conditions, with consecutive steps taken on it. The output signal is given in Figure 5a, as measured with a 10 MΩ probe. The average voltage rise for each peak is around 50V. The shift in the signal is due to charge flow through the probe, since its impedance is not infinite and it does not insure open circuit conditions.

In order to store the generated energy, we connect the tile to a diode bridge and a 10 µF capacitor. The result is given in Figure 5b, and shows that the capacitor charges in two stages up to 13V when taking one step on the tile. The initial rise is due to the user stepping on the tile and the second is due to the foot being lifted.

We estimate the stored electrical energy using the capacitor formula:

$$E_{el} = \frac{CV^2}{2} = 0.84\ mJ$$

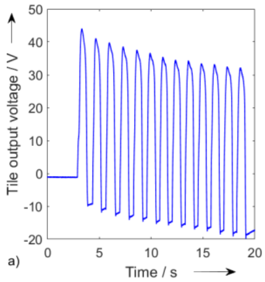

Figure 5. a) Output signal of the 50x50 cm^2 tile as measured with a 10 MΩ probe; b) Charging of a 10 µF capacitor with one step through a diode bridge.

The electrical energy generated with one step is thus slightly below 1 mJ. An electrolytic capacitor rated at 63 V has been used for the experiment. The main reason behind this choice is the large storage voltage limit, allowing for comparison between various energy harvesting modules.

As confirmed by visual observations, not all the piezoelectric elements are well deflected in this configuration. The thin steel sheet bends on the edges, and fails to actuate as required the peripheral membranes. To enhance the actuation, an 18 mm thick wooden tile has been added to the sandwich, under the steel sheet, as presented in figure 6. The new total thickness is 25 mm, with the active layer accounting for 4 mm.

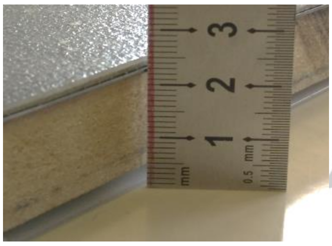

Figure 6. Energy harvesting tile with additional 18 mm wooden slab.

Measurements have been performed once again in similar conditions. The output signal, and the capacitor loading are shown in Figure 7. The average voltage rise for a peak is 82 V, significantly higher than in the previous case. As for the storage voltage on the same capacitor, it rises to 22 V per step. This corresponds to 2.44 mJ of electrical energy, a 3 time increase compared to the previous configuration.

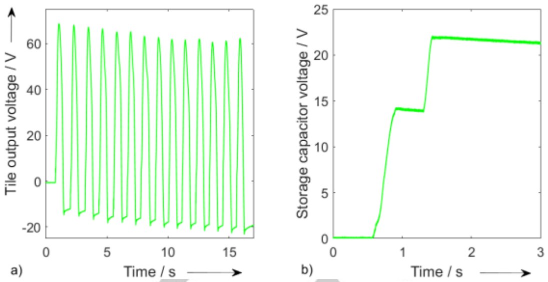

Figure 7. a) Signal of the tile after inserting a 18 mm wooden slab for more efficient actuation; b) 10 µF capacitor charging through a diode bridge.

This study shows the importance of transmitting the force efficiently to the active elements. It was visible with the naked eye that peripheral piezoelectrics in the tile had minimal deflection when the user stepped on the centre. Therefore, increasing the thickness of the actuation layer has proven to be an efficient approach to address that. When activated at a pace of 1 step per second this configuration would produce 2.44 mW of power.

Fatigue study.

A useful piece of information that flooring manufacturers collect is the fatigue behaviour of their products for quality and warranty purposes. Slip resistant flooring must show resilience in heavy traffic areas, therefore manufacturers perform tests upon production to insure a suitable quality. Usual tests involve performing 1 million walking cycles on a sample of flooring and observe the changes in texture and colour.

Within this in mind, we conducted a study on fatigue behaviour of the piezoelectric elements used in the energy harvesting tile. To do so, a membrane has been mounted onto a rigid frame and actuated with a cylindrical head for a large number of cycles. The test machine used is the Instron ElectroPulse E3000 system. The main elements of the setup are shown in Figure 8.

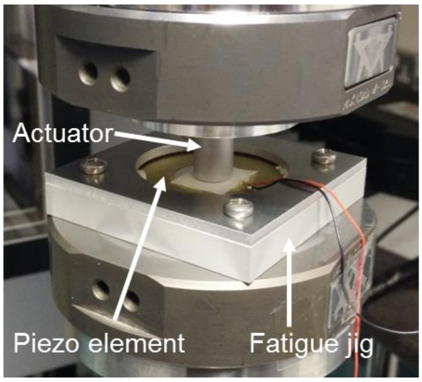

Figure 8. Compression fatigue test setup.

Up to 10 million repetitive compression cycles have been performed on the piezoelectric element with a 10 Hz actuation frequency. The deflection at the centre has been set to 1 mm, like in the tile itself, and the open circuit signal has been recorded. A sample signal is shown in Figure 9, with maxima reaching 64 V and minima -43 V, for a peak to peak amplitude of 107 V.

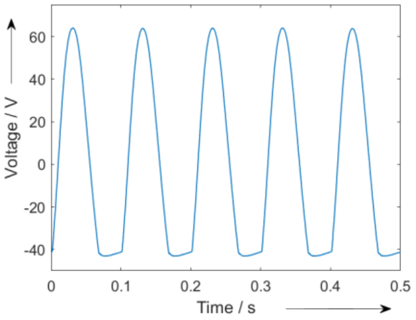

Figure 9. Sample piezo signal during fatigue testing.

The evolution of the signal maxima and minima is presented in Figure 10. The results of the first and last half of a million cycles out of 10 million are included. Little variation in the value of the peaks is observed. Indeed, the initial peak to peak signal amplitude is 109 V and the end amplitude is 110 V. A slight floating of the peak values can be observed, and it is most probably due to changes in ambient temperature in the test room, across the several day duration of the tests.

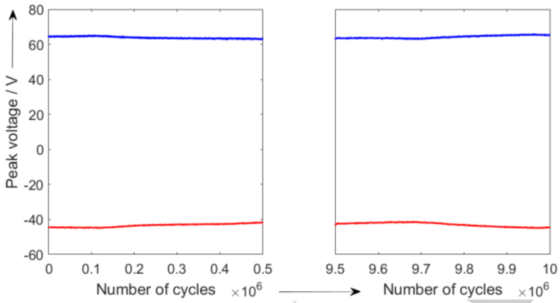

Figure 1. Evolution of the positive and negative piezoelectric peaks across 10 million fatigue cycles. The first and last half of a million cycles are presented. Little variation in the signal is observed, with a slight floating, most probably due to ambient temperature variation.

These results are highly encouraging for our technology, since they prove the reliability of the piezoelectric elements well above 1 million fatigue cycles, the usual mark in the flooring industry.

Intermediate discussion

These results conclude the first part of the study. To summarize, an estimation of the energy that can be recovered in a busy corridor has been provided, and an energy harvesting tile with commercially available piezoelectric elements has been fabricated and tested. Also, fatigue tests have been performed.

We have concluded from the busy corridor study that harvesting energy from steps is not an optimal solution for powering building systems, such as main lighting, heating or air conditioning. Building monitoring with low power sensors and powering low level lighting are suitable applications, due to lower energy requirements. In this context energy harvesting flooring will bring the benefit of autonomy, without the need for wiring to the mains. Thus, it will become possible to power devices in situations where mains electricity fails, is too expensive to connect to, or is not available at all.

Aiming at providing a benefit to the user through energy harvesting from steps is a more reasonable approach than aiming at generating energy for use at will. Rather than connecting energy harvesting floors to the grid, one would benefit from powering applications with low energy requirements, tailored to the generation capabilities of the flooring.

By using commercially available piezoelectric elements assembled into a 50 x 50 cm^2 tile we generate a few milli joules of electrical energy per step. This is sufficient for powering RF transmitters, allowing for the use of the energy harvesting floor as part of a presence detection/alarm system, for example.

Additionally, this study shows that the rigid tile format is desirable. Moreover, the thicker the top actuating plate, the higher the energy output.

With these conclusions in mind, it has been decided to direct the research towards devices for staircases, to power emergency lighting. This is to capitalize on the tile format, while providing a benefit in an area that is critical for the user.

In order to address the new use case, we decided to start by improving the efficiency of the piezoelectric elements. This was necessary so as to achieve compact devices that can provide enough power for emergency lighting.

Enhancing the power output with bistable piezoelectric elements

It has been observed that when a piezoelectric disc is subjected to high deflection, it reaches a state of plastic deformation. Initially the authors investigated this behaviour and its impact on the performance as a damaging mechanism. After a series of trials it has been found that under special forming conditions a piezoelectric disc reaches a bistable behaviour, similar to that of a push button.

An example of bistable piezoelectric membrane is shown in Figure 11. A concave shape is reached through controlled loading causing permanent deformation.

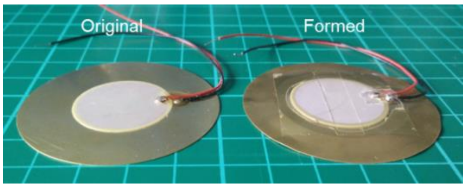

Figure 11. Piezoelectric disc in its original shape and formed disc showing bistable behaviour similar to a push button.

Contrary to the expectations, it has been found that as a result the output signal is significantly increased with respect to a flat disc operating in the elastic zone. A sample is presented in Figure 12.

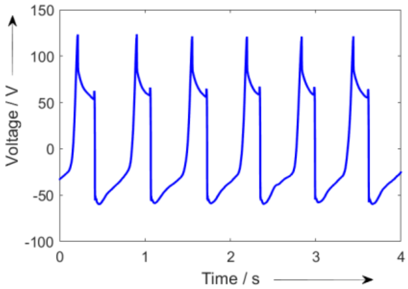

Figure 12. Signal of a bistable piezoelectric element.

Here the actuation frequency is around 1.5 Hz, with a negative peak value down to -60 V and a positive peak value up to 124 V. The resulting peak to peak voltage amplitude is 184 V, significantly higher than the signal of the flat piezoelectric membrane (107 V). One can notice the abrupt rise in voltage at each cycle, corresponding to snap action. The actuation force required is 19 N, as measured with a mechanical tests machine. This is similar to the force applied on a flat element to have 1 mm deflection.

Far from being damaging, the forming process yields piezoelectric elements with increased voltage for a force similar to that applied to a flat element. The signal is also repeatable, making it possible to integrate formed piezoelectrics into energy harvesting devices for stairs.

Design and performance of a device for stairs

When a person walks on stairs, they tend to step on the edges of the stair treads. Usually these edges are protected or at least highlighted with a stair nosing. Typically it comes as an L shaped profile that wraps around the edge. It can be made of metal, plastic, or a combination of the two.

The stair nosing has the role of providing slip resistance, visual contrast for the user, and protecting the edge of the tread. Since users tend to step on the edge of the treads, we decided to design a device that fits perfectly in this area.

We used a metal holding plate with circular slots, in which we placed bistable piezoelectric elements. We realised that it is possible to stack them for increased power output. Fourteen piezoelectric elements have been used to build the device presented in Figure 13. They have been placed on 7 slots, each containing 2 stacked piezoelectrics with an actuator on top. The array is covered by a steel top plate that transmits the force from the user's foot across the whole surface.

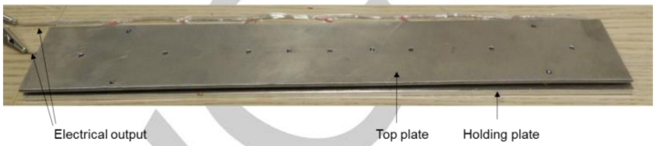

Figure 13. Energy harvesting device for stair nosings (40 cm x 6 cm x 1.2 cm).

The resulting device has a size of 40 cm x 6 cm x 1.2 cm. Having a thin profile, only 12 mm thick, it can be easily placed under existing stair coverings.

Capacitor loading tests have been performed to assess the electrical output. As previously for the energy harvesting tile, a circuit consisting of a diode bridge and a 10 µF storage capacitor is used. A screenshot of the capacitor loading with one step is given in Figure 14.

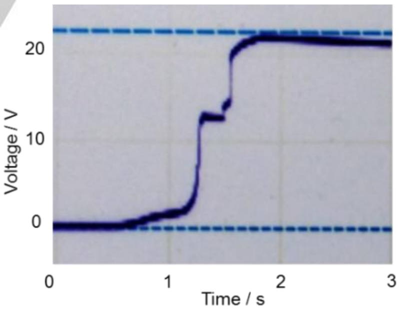

Figure 14. 10 µF capacitor loading per step with the stair nosing device.

The voltage reached is 22.5 V, corresponding to 2.53 mJ of electrical energy. This is slightly higher than the energy supplied by the energy harvesting tile with a wooden slab on top, and a total thickness of 25 mm. Moreover, the surface area of the stair nosing device is 10 times smaller, and only 14 piezoelectric elements are used, as opposed to 56 for the tile. This corresponds to an increase in energy per piezoelectric by a factor 4, proving the merit of forming piezoelectric membranes.

Integration into a staircase to power emergency lighting

The new device is ideal for integration into a staircase. To capitalize on its thin form factor, it has been fitted to a set of steps built for purpose, as presented in Figure 15.

The demonstrator is composed of two steps and an additional riser (Figure 15a). The energy harvesting nosing is placed at the edge of the first step (Figure 15b). A power management circuit is placed close to the next riser. It is composed of a bridge rectifier connected to a capacitor followed by a DC-DC converter. A voltage regulator allows setting the output to the desired level. The power management circuit rectifies the signal coming from the harvester to power the component of our choice. Here, we use a 5000 K white LED, with an adapted resistor. The LED has been chosen for its high efficacy, and it is placed at the top of the last riser, as shown in Figure 15a. PVC stair coverings are placed on top of the steps. They provide slip resistance and conceal the energy harvesting system.

When the user steps on the first tread, the LED turns on and lights the second one. The light output is shown in Figure 15 c. With this particular energy harvesting device, 0.9 s of light are generated per step. The illuminance created is around 1 lux and corresponds to the level required for emergency lighting on staircases[15].

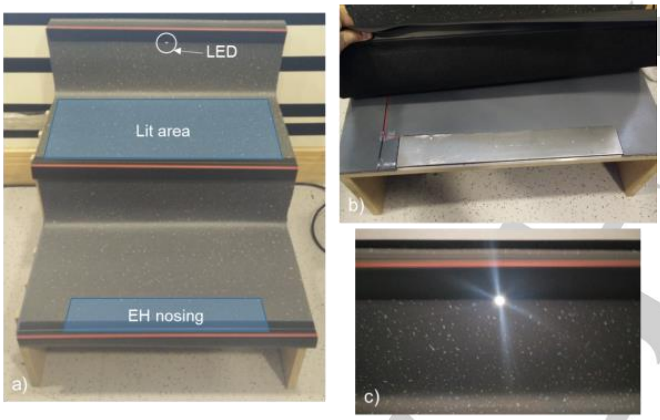

Figure 15 a) Staircase with embedded energy harvesting nosing and a high efficacy LED; b) energy harvesting device placed under the stair covering; c) light generated with one step.

This is the first complete demonstrator, containing all the parts required for an energy harvesting system. It is capable of providing a benefit to the user, one step being sufficient to trigger emergency lighting.

Although the functionality of the system and of the formed piezoelectrics has been proven, it has been decided to improve the energy output further. This next step involves minimizing the passive area of the piezoelectric elements.

Preloading piezoelectrics to further increase energy output and density

The authors decided to reduce de passive brass area that surrounds the active piezoelectric ceramics. To do so, square patterns have been cut around the latter, keeping the brass surface close to the necessary minimum, as depicted in Figure 16. This allowed for an overall decrease in surface area by a factor 3.14.

Forming not being practical on the new elements, it has been decided to preload the membranes laterally to provide them with a 3D shape. This was achieved by clamping square elements on the sides and applying lateral force inside a bespoke thin holder. It has been observed that under these conditions the piezoelectric element buckles, as presented in Figure 17. By doing so, it becomes bistable, thus allowing multiple actuations, each followed by self-return to the initial position. In short, the pre-loaded square elements have a similar behaviour to formed elements, with the added benefit of much reduced surface area and mechanical noise. Indeed, the snapping of the formed membranes was accompanied by a clicking sound, while in the new conditions the sound is not perceptible anymore.

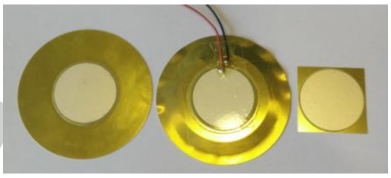

Figure 16 From left to right: flat, formed, and pre-cut piezoelectric element.

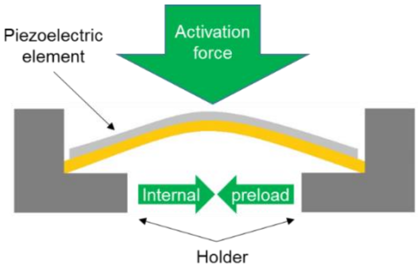

Figure 17 Schematic section of a preloaded piezoelectric. An internal preloading mechanism induces buckling in the initially flat square element. In use, the actuation force is transmitted from the top.

Having the new configuration in place, we measured the energy generated per piezoelectric element, and we compared it to the previous cases. Like before, the comparison has been done by observing the loading of a 10 µF capacitor with one actuation. The results are summarized in Figure 18.

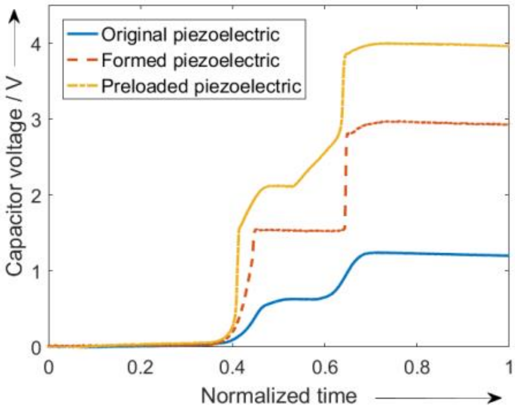

Figure 18 Capacitor loading with one press for 3 types of piezoelectrics.

The original piezoelectric loads the capacitor to 1.2 V, and the preformed one to 3.0 V. In terms of stored energy this is a 5.7 times increase. The preloaded piezoelectric charges the capacitor to 4.0 V, which is a 10.3 time increase with respect to the original element. Given that the surface area of the preloaded piezoelectric is 3.14 times smaller, this translates into a 32 times increase in energy per unit area and per activation.

This design has been used to fabricate a new generation of energy harvesting devices for stairs.

Upgraded energy harvesting devices for stairs

A new design for energy harvesting devices has been proposed around preloaded piezoelectrics. Fifty-six piezo elements have been assembled together onto a CNC machined aluminium holding plate. They have been separated in two parallel lines, each one preloaded laterally before use. The resulting device is presented in Figure 19. A commercially available aluminium stair nosing is used as top plate to actuate the piezoelectric elements. It is covered with white plastic strips for slip resistance and visual contrast purposes. End caps are used to hold all the parts together and stabilise the structure.

The overall dimensions of the prototype are 40 cm x 9 cm x 1.35 cm. The 1.35 cm total fitted thickness is composed of the active part thickness (8.5 mm) and top aluminium nosing thickness (5 mm). The nosing riser is 32 mm high, and contains the LED in the middle. The latter lights the step below when the device is activated.

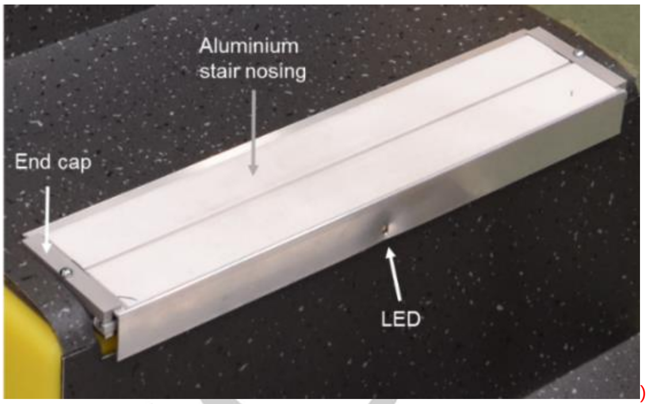

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Figure 19 Energy harvesting stair nosing mounted on a step. The aluminium stair nosing actuates preloaded piezoelectrics placed underneath (not visible on the image). End caps stabilise the structure.

Capacitor loading through a diode bridge with the new prototype is shown in Figure 20. Given the increase in generated energy, a 47 µF storage capacitor is used. The voltage on it reaches 27.5 V per activation, which corresponds to 17.7 mJ of electrical energy. This is a 7.3 times increase compared to the 50x50 cm^2 tile with wooden slab actuator that has the same number of piezoelectrics. As for the energy density per unit area, it increased 51 times reaching 0.49 J/m^2.

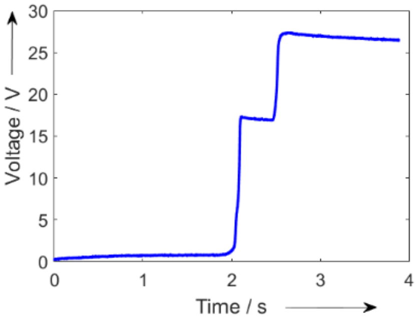

Figure 20 Charging a 47 µF capacitor with a device based on preloaded piezoelectrics. A storage voltage of 27.5 V is reached, corresponding to 17.7 mJ of electrical energy.

The emergency light output has been tested with the new device. To do so, it has been connected to the white LED presented previously through the power management circuit and a series resistor of 1.2 kΩ. The output voltage of the circuit was regulated to 3 V, the nominal threshold voltage of the LED being 2.5V. As a result, 10.6 seconds of light at emergency levels have been generated per activation, as depicted in Figure 21 a. A photograph of the light beam when the device is in use is given in in Figure 21 b.

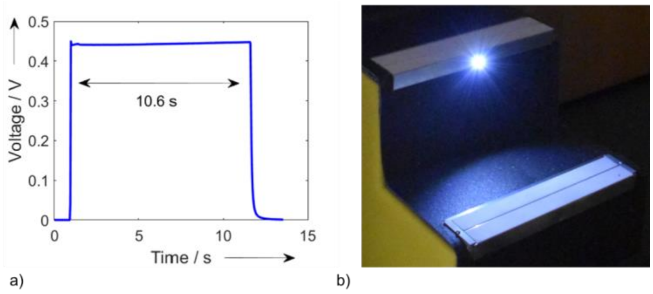

Figure 21 Light output with an enhanced stair nosing: a) voltage on the series resistor of the LED after one activation of the energy harvesting stair nosing. The square pulse corresponds to 10.6 s of current and thus light output; b) photograph of the light beam as seen in a dark environment.

Since the current intensity is the same as observed with the demonstrator based on formed piezoelectrics, it is safe to say that we witness a 12 time increase in lighting duration, up from 0.9 s recorded previously.

Work has also been conducted on a multistep system capable of tracking the user and lighting the necessary treads in front of him. Details on this system will be revealed at a later stage.

Discussion

The demonstrators and results presented here prove the viability of energy harvesting stair treads as a solution to power emergency lighting. To achieve this, it has been necessary to improve the power output and energy density of existing piezoelectrics by forming or preloading. A design of experiment was necessary at each stage to find the best conditions in which the active elements perform. Each of the two kinds of stair nosing prototypes are the end version of an iterative design process aimed at increasing energy output while reducing complexity and cost.

The final device design, as presented in Figure 19, is composed of parts that can be manufactured by extrusion, just like the ubiquitous aluminium stair nosings. Therefore, adapting the devices to the width of a given set of stairs is as easy as cutting to size. Internal electrical interconnexions are scalable as well, the only varying parameters with size being the number of piezoelectric elements and the assembly time.

Further optimization steps are possible to enhance the latter. Indeed, the 56 piezoelectrics used have been integrated individually into the assembly. To decrease this number longer shapes could be fabricated for our particular use.

The piezoelectric elements used in the present work have an affordable cost that can be further reduced through economies of scale. They are around 30 times cheaper compared to state of the art piezoelectric ceramics used for actuation in precision applications. In their unchanged flat disc shape, the piezoelectric elements used in the present article show a conversion efficiency of a few percent. Sate of the art ceramics are expected to have efficiencies up to 14%, based on their coupling factors, but are penalized by the high cost and some degree of fragility. The optimization methods used in the present work allowed increasing the efficiency of our piezoelectrics without negative impact on the cost. It is estimated that forming alone can increase efficiency up to 11%, reducing the gap with state of the art materials.

As mentioned previously, the energy harvesting modules are connected to a power management circuit that includes a rectifier and a voltage regulator. Since in every case the active energy harvesting layer will be surrounded with an underlay for thickness matching, the power management circuit can be conveniently housed inside the latter.

It is worth mentioning here that the energy our devices recover from steps is available for use immediately. Since they do not rely on inertia phenomena for temporary energy storage, the electrical energy builds up on the storage capacitor just as the user steps on a tread.

Also, any force applied to our active nosings will result in energy generation. This means that the present devices cater for a large number of users. There is a sense though that a threshold force will be required to obtain light output. This is due to the fact the power management circuit consumes a part of the charge to become operational. The threshold force required to achieve this must be measured and added to the operational parameters of the devices. As it stands, an average user generates enough energy to trigger an LED with ease, which indicates that the threshold force is rather low.

As compared to existing electromagnetic energy harvesting tiles, the devices developed in the present work are much thinner: 1.35 cm total thickness, as opposed to 7 – 10 cm for devices available on the market. Although not verified by the authors, the efficiency is expected to be higher for the latter, given the use of electromagnetic conversion.

An advantage of the demonstrators developed here is that they do not use mechanical aids to help the piezoelectric components return to the initial position after step pressure is released. This is done through boundary condition control, which simplifies the device design, reducing the number of parts and failure sources.

It is worth noting that the devices are to be submitted to fatigue testing. The flat piezoelectrics used initially have an excellent fatigue resistance, as presented previously. Similar tests must be performed on the latest devices in order to monitor the behaviour of preloaded piezoelectrics and validate them for a large number of cycles. Validation for a small number of cycles has been performed though, with no detectable change in performance over 500 activations.

Another discussion point is regarding the units and quantities used in the present article. Energy is preferred to power since user’s steps are separate events as seen by the energy harvesting devices. Indeed, there is no predefined step frequency at which a harvester will be actuated, because local foot traffic can vary in a large interval, as shown in the busy corridor study. This pushes the authors to analyse individual events and the potential uses of the energy generated per event. In case the reader would like to estimate the power production for comparison purposes, it is enough to picture an environment and multiply the energy generated per step by the frequency of steps. For example, on a staircase fitted with the latest devices a user will generate

17.7 mJ per step. If they walk at a pace of 1 step per second, the resulting power will be 17.7 mW.

Conclusions

The present article describes the research journey towards the fabrication of stair devices capable of harvesting energy from steps to power emergency lighting.

The first demonstrator was a 50 x 50 cm^2 energy harvesting tile, capable of generating up to 2.4 mJ of electrical energy per step when fitted with a rigid top. It uses commercially available circular piezoelectric elements. These show an excellent fatigue resistance, reaching 10 million compression cycles without decay in performance.

It has been found that forming the circular piezoelectrics under controlled conditions improves the energy output 5.7 times.

A new device has been built capitalising on this. It is a 40 cm x 6 cm rectangular harvester, to be placed under a stair nosing. The device has been fitted into a demo staircase with 2 steps and an additional riser with an embedded LED. The harvested energy is fed into a bespoke power management circuit that produces a regulated voltage for the LED. The harvester generates 0.9 s of light at emergency levels upon activation.

Further optimization has been performed on piezoelectric elements by cutting out the active part and submitting the resulting shapes to lateral loading. This increases the output energy 10.3 times compared to the initial circular elements. Since the surface area of the new shapes is 3.14 time smaller, this translates into an increase of energy density per unit area by a factor of 32.

A new device has been built using this finding. It is composed of an active layer containing preloaded piezoelectric elements, activated by a commercially available stair nosing placed on top. A LED is embedded in the middle of the nosing riser to light the surface below. The footprint of the device is 40 cm x 9 cm, for a total thickness of 13.5 mm, with 8.5 mm for the active layer. This device generates 10.6 s of light per actuation in the same conditions as the previous prototype, bringing a factor 12 increase in light output.

Future developments for the present technology are optimization for quicker assembly, fatigue testing, and live deployment.

Experimental Section

Throughout the present work care has been taken to measure the piezoelectric signals or voltage on the capacitors being charged using high impedance probes. This is necessary because of the high output impedance of the piezoelectric elements or assemblies. To minimize the impact on the measurements, 10 MΩ probes have been used in all the experiments.

A buffer circuit has also been tested for lossless measurements. Although having a very high input impedance, it does not allow high input voltage, and thus hasn't been used for the measurements presented here. This is a suitable tool for observing the pyroelectric effect, which is outside the scope of the present work.

Fatigue testing has been performed in a room with controlled ambient temperature dedicated to mechanical tests. The piezoelectric output signal has been recorded with a Pico series oscilloscope, allowing to store waveforms for a large number of cycles. In the test procedure, the piezoelectric membrane is initially actuated to a deflection of 0.5 mm. Cyclic deflection with am amplitude of 0.5 mm is then performed around this point, for a peak to peak centre deflection of 1 mm. The data sampling rate has been adjusted to 400 samples per second: the minimum required for a correct reading of the peak to peak voltage amplitude, so as to decrease the amount of recorded data points and increase the number of recorded cycles.

Measurements of force during gait have been performed using an AMTI force plate. The user under observation has been given enough space to reach his normal walking speed before stepping on the force plate. He was also allowed to step a few additional times afterwards, before slowing to a stop. Series of several tens of measurements have been performed for the left and right foot, with representative samples shown in Figure 1.

People counting in a busy corridor was performed with an Axis M30 network connected camera, and the data stored on a personal computer. The camera has been installed in the ceiling, on a straight portion of a university corridor with high footfall.

Acknowledgements

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Keywords: energy harvesting • floors • stair nosing • piezoelectric element • emergency lighting

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Captions:

Figure 1. Forces developed when stepping. Measurements for the left and right foot of the subject are presented, as recorded with a force plate. The subject weight is 87 kg.

Figure 2. Traffic in a busy university corridor, as recorded by an optical counting system.

Figure 3. Structure of the energy harvesting tile active layer: a) commercially available piezoelectric element as used in the assembly; b) active matrix of 8x7 elements on a flexible substrate; c) structural detail. Spacers are used for actuation purposes. Air gaps are left below the piezoelectric membranes to allow for deflection (not shown).

Figure 4. 50x50 cm^2 energy harvesting tile with embedded LED strips. The total thickness, including the slip resistant upper layer, is 7mm.

Figure 5. a) Output signal of the 50x50 cm^2 tile as measured with a 10 MΩ probe; b) Charging of a 10 µF capacitor with one step through a diode bridge.

Figure 6. Energy harvesting tile with additional 18 mm wooden slab.

Figure 7. a) Signal of the tile after inserting an 18 mm wooden slab for more efficient actuation; b) 10 µF capacitor charging through a diode bridge.

Figure 8. Compression fatigue test setup.

Figure 9. Sample piezo signal during fatigue testing.

Figure 2. Evolution of the positive and negative piezoelectric peaks across 10 million fatigue cycles. The first and last half of a million cycles are presented. Little variation in the signal is observed, with a slight floating, most probably due to ambient temperature variation.

Figure 11. Piezoelectric disc in its original shape and formed disc showing bistable behaviour similar to a push button.

Figure 12. Signal of a bistable piezoelectric element.

Figure 13. Energy harvesting device for stair nosings (40 cm x 6 cm x 1.2 cm).

Figure 14. 10 µF capacitor loading per step with the stair nosing device.

Figure 15 a) Staircase with embedded energy harvesting nosing and a high efficacy LED; b) energy harvesting device placed under the stair covering; c) light generated with one step.

Figure 16 From left to right: flat, formed, and pre-cut piezoelectric element.

Figure 17 Schematic section of a preloaded piezoelectric. An internal preloading mechanism induces buckling in the initially flat square element. In use, the actuation force is transmitted from the top.

Figure 18 Capacitor loading with one press for 3 types of piezoelectrics.

Figure 19 Energy harvesting stair nosing mounted on a step. The aluminium stair nosing actuates preloaded piezoelectrics placed underneath (not visible on the image). End caps stabilise the structure.

Figure 20 Charging a 47 µF capacitor with a device based on preloaded piezoelectrics. A storage voltage of 27.5 V is reached, corresponding to 17.7 mJ of electrical energy.

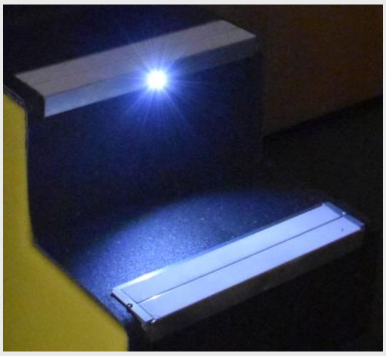
Figure 21 Light output with an enhanced stair nosing: a) voltage on the series resistor of the LED after one activation of the energy harvesting stair nosing. The square pulse corresponds to 10.6 s of current and thus light output; b) photograph of the light beam as seen in a dark environment.

Entry for the Table of Contents (Please choose one layout)

Layout 1:

FULL PAPER

Light from steps: We developed energy harvesting devices for stairs to power emergency lighting. Our stair nosings convert mechanical energy from steps into electricity using piezoelectric materials. An active energy harvesting layer is placed under the stair nosing to power a LED that lights the step in front of the user. A light pulse with a duration of 10 seconds is generated at every activation.



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Powering lights with piezoelectric energy harvesting floors

Layout 2:

FULL PAPER

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