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THE *ITUR* SAFETY KIT

From prototyping to manufacturing of an off-grid lighting device to be retrofitted within existing industrial metal stairs for STF *prevention*

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Abstract. Following the Health and Safety Executive report twenty five percent of accidents per year in the manufacturing sector are related to slips, trips and falls (STF), involving significant costs for employers. Two of the main reasons for accidents are slippery steps, stairs or ramps, and stairs or passageways that are poorly lit. The following paper presents a preliminary evaluation of moving from prototyping to manufacturing of a designed safety kit, the *iTUR*, which aims to prevent SFT injuries. This device has been developed over the past three years throughout the design and testing of a series of devices investigating renewable power generation through piezoelectric sensor technology for LED lighting output. The iTUR has been designed to be easily retrofitted within existing metal stair treads as a stand-alone power unit. By activating the lights when stepping on the stair tread the user is guided along the staircase. In case of slippery conditions, lights change in color and frequency providing a dynamic real-time warning reminder to the user. The device is low-cost presenting minimum electronic and mechanic parts and it is easy to attach to existing metal treads. Further challenges relate to the development of a robust marketing strategy and a business model estimating the initial number of costumers and profit margin per year.

Keywords. STF injuries, piezoelectric technology, lighting

1. Introduction

After lifting and handling injuries, Slips, Trips and Falls (STF) are the third most common causes of accidents in workplaces accounting for approximately 13% of the injuries in all workplaces (Work Safe ACT, 2010). These accidents largely affect both employer and employee with costs that depend on the gravity of the injury. Significant costs relate to lost workdays and workers compensation payments for the amount of millions every year the employers (Safety First, 2002). In the worst-case scenario, serious injuries could require a long-term treatments or even lead to the death of the employee. These accidents not only have material costs but also can significantly affect the quality of life, having major psychological consequences (QBE, 2006). When focusing on falls, most of the accidents happen from low heights such as steps or stairs (Work Safe ACT, 2010). Two of the main reasons for accidents are the following:

- Stairs or passageways that are poorly lit
- Slippery steps, stairs or ramps

The proposed iTUR kit, designed as a stand-alone power unit to be retrofitted within a metal stair tread, addresses both of the above issues with the aim of providing a safer environment. The kit has been developed considering the integration of piezoelectric sensor technology as energy harvesting system and focusing on power optimization for LED lighting output. Power optimization is informed by an efficient power circuit and the integration of mechanic components aiming to facilitate and improve the conversion of force of footstep to the needed movement triggering the sensor (performing when in vibration).

The device is designed as unit to be integrated within one stair tread. Each unit comprises of multiple modules, each module including one piezoelectric sensor connected to the electronic circuit and to the LED light (Fig.1).

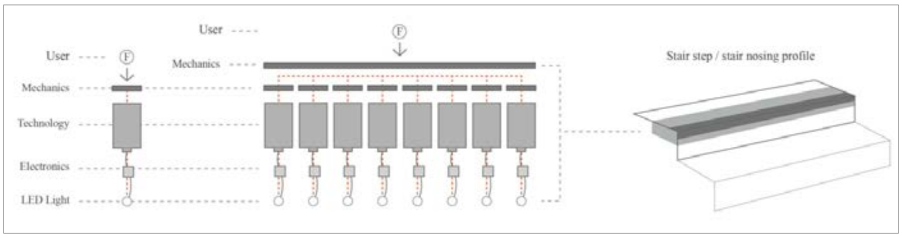

Figure 1. iTUR safety kit unit and modules per stair tread

This paper discusses two major assessments undertaken along the development of the proposed safety kit. These evaluations are not taking into consideration the economic sustainability of the device but the challenges in achieving the needed energy output to provide the service, safety lighting, without compromising the user’s comfort. The first one describes a preliminary installation of the device along metal stairs at University of Melbourne

Parkville campus with the aim of measuring real-time power generation considering the applied force of footstep. This evaluation has been done by testing one module: one piezoelectric sensor connected to electronic circuit and to LED light. The second one illustrates an investigation undertaken in collaboration with electronic engineers and lighting designers simulating the integration of three units within three built stair treads with the aim of evaluating user comfort and safety. The prototype is designed and tested considering a physical displacement of the tread needed to activate the sensors underneath as well as LED lights number, disposition and initiation (dynamic reminder). An initial presentation of related work describes the potentials of piezoelectric sensor technology for the purpose of lighting and related design challenges.

2. Related Work

Specific interest has been given to research in kinetics for energy harvesting and the opportunity of capturing energy from the human motion providing electricity for devices (human powered devices) (Starner, 1996, Shenck & Paradiso, 2001). This technology focuses on harvesting energy from mechanical excitation coming for example from walking or running (footfalls produce <67W). Examples of this technology are found in microelectromechanical systems (MEMS) such as piezoelectric and electromagnetic that have emerged as prominent research fields in engineering covering several aspects such as modelling, materials, device design and circuits (Priya, 2009). These two technologies performing following the same principle differ in the way of operation as well as in the size and occupied space. The Piezoelectric effect is the capability of certain material to generate alternating current (AC) from mechanical stress, when bent, squeeze, twisted or in vibration then to be converted into direct current (DC) (Kazmiersky, 2011).

Piezoelectric technology generates voltage when deformed. By definition piezoelectricity is the electric polarization in a substance resulting from the application of mechanical stress (Oxford Dictionary). Piezoelectric technology has been fascinating researchers for many years, mostly focusing on the development of new piezoelectric materials and sensors. All piezoelectric sensors 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 (Yang, 2009). There are over two hundred piezoelectric materials that could be used for energy harvesting sensors, with the appropriate ones being selected for each application (Das, 2012). Despite the early discovery of the piezoelectric effect in late 1800 by the brothers Curie, piezoelectric devices application and performances increased throughout the following century thank to new man-made material development especially in USA, Russia and Japan (Priya, 2009). 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 (Das, 2012).

The integration of piezoelectric sensors technology have been explores Projects such as the Club Watt in Rotterdam (2008) and the ones presented in the Regenerative Infrastructure Competition (Land Art Generator Initiative, 2013) mostly aim to promote a broader intellectual awareness and education on renewable energy harvesting technologies investigating users' active engagement in the generation of power. On the other hand design propositions that use electromagnetic technology such as the Pavegen tiles installed at the London Olympic, or the piezoelectric sheets installed within a public transport interchange in Tokyo (2008), moved to a higher level of design investigation by using the technology not only in a symbolic manner but with a more specific functional purpose, considering for instance the possibility of generating electricity for street lighting using LEDs. However whereas electromagnetic systems such as Pavegen requires a specific contained volume in order to perform, piezoelectric sensor technology are of great interest due to their small form factor and high efficiency rapidly increasing during the past few decades (source) . Thus in consideration of future design applications, piezoelectric sensor technology presents the perfect ground to begin design investigations.

3. iTUR Energy Output

The efficiency of the proposed iTUR kit is initially tested considering possible power output installing one module (one sensor, one electronic circuit and one LED) along metal stairs at University of Melbourne Parkville campus (Fig. 2). The purpose of this test is to gather a preliminary data about energy production as well the understanding of LED lighting application in real time. The metal stairs were chosen as site to test the device because presenting as well the opportunity of evaluating flexibility properties of the metal material, or its capability of bending repetitively when force of footstep is applied triggering vibrations strong enough to activate the sensor. In this scenario advantages are the costs related to the device itself considering the reduction in mechanic components, and to the integration of the device along the stair tread considering none construction work.

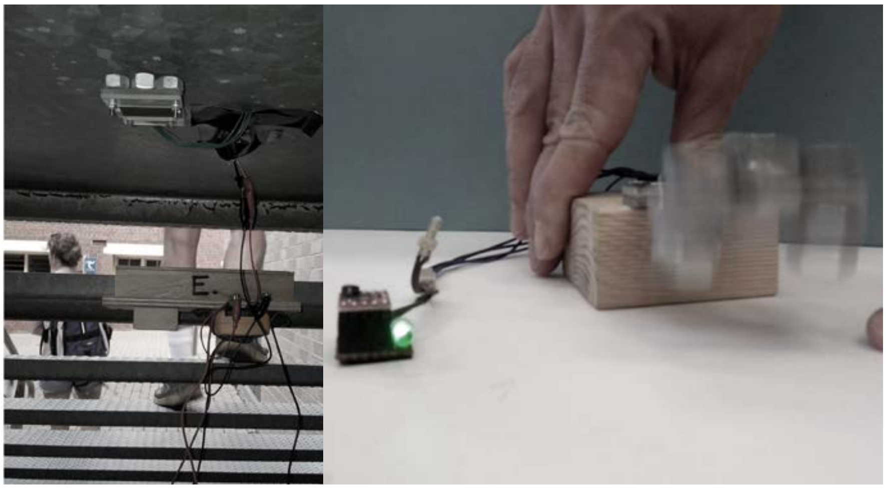

Figure 2. Placement of the device underneath metal stairs

The profile of the metal stair allows placing the device in different positions underneath the treads, hidden from the user view in order to not affect individual behavior when stepping. In order to collect data related to energy production, the LED was connected to a multimeter measuring the output in voltage and sending the information to a computer (laptop) located few meters away. Due to an unstable wireless signal, the data was gathered several times. As an example, the proposed graph in Fig. 3 shows the instantaneous energy output during a 25 minutes time frame (reaching a peak of 2.4 volts).

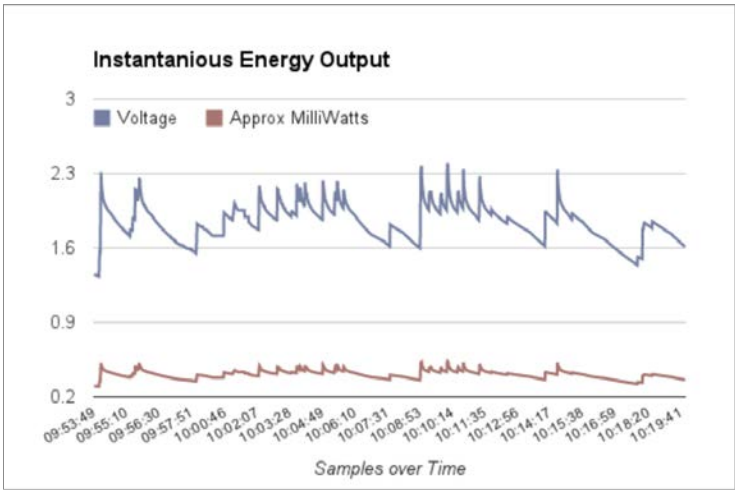

Figure 3. Real time power generation from footstep

Even if always below 3.5 volts, the LED is lighting up at every step. However when below this threshold it becomes more difficult to predict the value of the current. Considering an approximate evaluation, the total amount of energy generated equal to 596 millwatts (per one module). Then this value can be multiply per the number of sensors placed along one tread and related LED lights.

Once having an understanding of the energy produced by one module, the next phase begins investigating the number of modules per unit considering the required space occupied by each module, mode of activation considering force of footstep, as well as the needed number of LED lights per stair tread (Fig. 4).

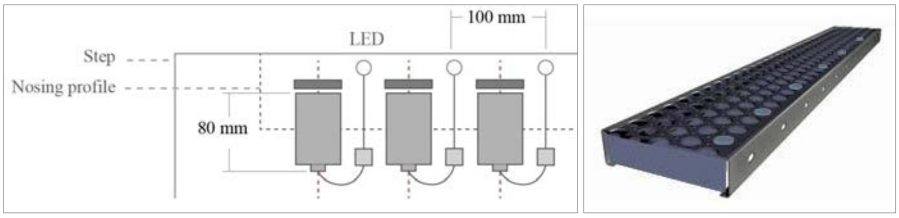

Figure 4. Diagram of modules distribution along one stair tread

In considering the design of the unit and the integration of multiple modules generating power independently, the challenge becomes how to activate all modules simultaneously in order to have the distributed number of LEDs on at the same time. This implies the use of an additional mechanic device to be placed on the topside of the modules able to redirect the force how and where wanted based on where the footstep is applied. The device could be easily retrofitted when considering perforated metal stair treads. Other aspects are considered when designing the external surface of the stair nosing profile in view of a direct contact with the user footstep. The selected material is thought to be strong enough to resist to the continuous up and down movement and protect the overall electronic systems underneath.

4. iTUR Safety and Comfort

User comfort and safety is tested with the construction and assessment of a three stair treads prototype that simulate the integration of the designed unit including a mechanic device (for physical displacement) and LED lights. For the purpose of this investigation considering the limited access to equipment, the prototype has been built in plywood material. The three stair treads prototype is designed to have three steps made of 12 mm plywood considering, each step following the standard dimensions of h165mm x w300mm x l600mm. In testing comfort two modes of displacements are proposed:

1. Magnet snapback tread: a controlled displacement of the whole stair tread considering 3, 7 and 10 mm allowing the step to rotate having the extremity closer to the riser fixed;
2. Spring loaded tread: a variable displacement of a channel insert in the stair tread by positioning springs, and considering a total displacement given by the type of spring and additional values depending on the applied weight. The channel is located closer to the stair nosing profile.

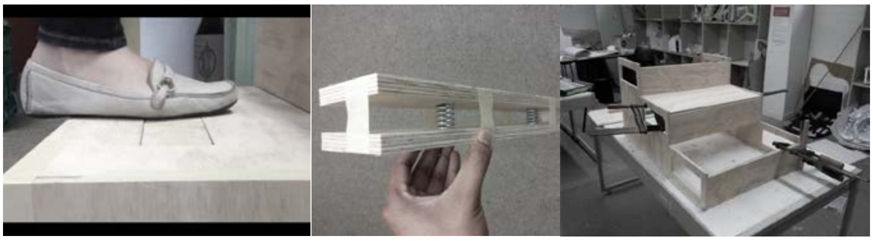

Figure 5. Three stair treads prototype and the spring loaded mode

The design of the prototype is thought to be flexible enough to allow both mechanisms to be tested without major assembling/disassembling work. In the beginning two lateral frames are designed considering openings in order facilitate adjustments and/or the introduction of additional parts, such as structural components and lighting circuit, once trades and risers are in place. Moreover these openings provide a different visual understanding of the mode of displacement from underneath the step. The three risers and the back support are slotted then into lateral frames. Treads are thought as replaceable parts considering the two design options for the needed displacement. Based on preliminary testing after the construction, the stair treads resulted to be structurally unstable at the joint point between the tread and the riser. Infact when a footstep is applied the tread deflects in the middle calling for additional support. Ofsetting the lateral step profile, two additional frames are located considering accommodating as well both modes of displacement.

There are two major differences when considering the two modes of displacement proposed that affects user comfort. The first aspect refers to the user awareness of the device in place and directly involves the design of the tread, in other words how visible is the integrated kit. When in the magnet snapback tread mode the whole tread is moving, in the spring loaded tread mode a channel is visibly cut from the step. When stepping on the stairs the user might be inclined to locate the foot on the top of the channel or away from it, depending on the user subjective reaction. The second dissimilarity comes from the way the two mechanisms operate. The channel mechanism is an on/off state where the displacement is set independently of the user control but dependent on how much force is applied and where. Moreover, multiple displacements can occur by having the user standing on the step and slightly shifting the pressure point applied by the footstep without having to step up from the tread. Due to the way springs operates it becomes however more difficult to be accurate in measuring the displacement, knowing only what the maximum movement can be considering the maximum compression of the selected spring (with this type is 10 mm). With magnets the mechanism is either on or off and the height of the displacement is always given (not depending on the applied force or foot position). In fact, once the user steps the first time on the tread then the foot has to be fully removed before stepping again, allowing the tread to go back to is initial position. In view of the possibility of retrofitting the existing metal stairs, the channel mechanism is considered as the most suitable.

4.1 TREAD UNIT DESIGN: SPRING LOADED CHANNEL AND LED LIGHTING STUDIES

The design of the unit (one stair tread) considers the integration of the channel connected to LED lighting and preliminary studies on lights number, and placement.

The channel is located few centimeters away from the stair nosing profile, each channel is 70 mm wide and 400 mm long comprising two springs and protruding over the tread of 5 mm. The design of the channel has been developed having in mind an effective mode of easily retrofit existing stairs. At this stage, the depth of the channel is still preliminary and being challenged during the development of the mechanics (the depth is a key aspect for retrofitting). However, the width and length are here tested considering preliminary position and dimensions of a footprint. In fact within the specific area of the tread, the walkable surface is usually limited within a smaller portion of the step. By having the displacement operating with springs, a shorter dimension of the channel compare to the footstep might increase the level of user stability (and thus comfort). At this stage only two springs are integrated to simulate the displacement. However the number might change in future testing following mechanics development and the idea of using the spring for a double purpose: displacement and sensor vibration. Black tape is used for stabilizing the spring in position and for visually differentiating the channel from the rest of the tread. Even if at the moment the number of tape strips does not necessary implies a correspondent number of sensors, this design raises questions on the benefit of visualizing the channel and the related system underneath.

The channel mechanism is thought to be the trigger of the sensors thus in this prototype the one for the LEDs. For preliminary lighting studies a system is built with an external power source (battery) that can simulate how the energy harvesting sensors perform and demonstrate what at this stage could be feasible to assess from a point of view of lighting. The LED lights selected are 1.8 volts, 5 mm round module, and used in real time. Lighting output is investigated considering the following:

- Number, position and color of LEDs considering have four separate segments of lights (5 each)
- Type of light patterns: simulating the amount of energy output and considering LEDs fading effect
- Type of switching mechanism with a dimmer

Initial discussion is made in regard to the overall performative aspect of the lighting system in regard to footstep action considering number of lights per step, switching modes and possible integration of Arduino technology to make the system more dynamic (however that would require additional power to operate at this preliminary stage is not evaluated).

Taking into consideration these preliminary thoughts, multiple segments of LEDs are considered to be the most suitable solution having still the opportunity of activating only some of them depending on where the footstep is placed (multiple points of contact). Having estimated the number of sensors underneath each step being between ten to fifteen, and each sensor lighting one LED, the number of lights considered is the same. For the purpose of this first test a simple model is developed considering real-time lighting output with a switch controller (three switching sensor in one of each stair tread) and segments of lights positioned along the tread (near the nosing profile). When walking up the stairs the step the LEDs are lighting always in from of you (the following step). The presented test is a preliminary one, taking place within an enclose space with the purpose of controlling the brightness of the surrounding environment. The population of the experiment consists of 20 users, faculty and students at University of Melbourne. Each user is asked to enter the room and walk up the stairs for several times within a 30 seconds time frame. After completing the activity each user is then asked to answer to a questionnaire related to comfort in walkability and lights visibility. The test is recorded using two video camera positioned in two different angles. When one camera aims to record only the user footsteps, the other camera records the whole user body movement.

After reviewing each of the items of the questionnaire, the overall findings show that the proposed physical displacement and number of LEDs were providing a pleasant and comfortable environment. However, additional evaluation needs to be taken in consideration of lights position and activation in relation to where the force of footstep is applied. Having the prototype designed and built the following investigations are also considering a more dynamic performance of the LEDs, evaluating changing in lighting intensity and colour.

5. Conclusions and future steps

The proposed assessments were conducted to preliminary evaluate the potentials of the iTUR safety kit in providing the needed power output and user comfort and safety, as well to define a preliminary design of the proposed unit to be integrated along one stair tread. The design is in process to be further developed and tested considering optimization of the electronic circuit thought to be connected to multiple sensors as well as the reduction of the mechanic components. Having the interest of Melbourne City Council, additional design applications for the proposed kit consider its integration along poorly lit public staircases near major public transport hubs. In this scenario the power generated is also thought to be stored during the day (having thousand of pedestrians moving through a specific location during peak-hour time) and use it when needed at night. Moreover the power generated could be additionally use for other purposes such as pedestrians' counting and wireless data communication.

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