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## Energy harvesting materials

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Thanks to the Faculty Development Grant I was able to gain a better understanding of energy harvesting materials and the smart textile market in general. Energy harvesting materials have the ability to scavenge available ambient forces such as mechanical motion, vibration, motion induced by natural forces such as wind and water, light, and radio frequency (RF) to generate electric power. FDGA funding helped me collect valuable information to generate a report on current advancement in energy harvesting materials with the most potential to be adapted for apparel products. The report discusses the challenges and offers a design perspective on optimization of the materials; it also opens possibilities for publication in the near future. The research process involved interviewing scientists and designers specialized in wearable technology, studying scientific journals and attending advanced material conferences. It also helped me create a network within the field and connected me with scientists who expressed interest to establish interdisciplinary collaborations.

## WHY ENERGY HARVESTING?

Energy harvesting materials have been studied since the 90s[1,2] and their application for smart textiles goes back to 2007.[3] Scientists have been continuously improving upon their application to clothing, taking into consideration needs that are unique to the human body, such as flexibility, breathability, dimension, washability, and durability. This field of this research is important because it will eventually make wearable electronics autonomous from heavy batteries, the elimination of which would be especially beneficial to military personnel and patients dependent upon physiological monitoring. Milad Afshar, Director of Energy Harvesting and Storage at Myant Inc., expressed the potential contribution of this technology to sustainability when he stated: "we have a number of low-power-consuming portable electronics, such as Bluetooth transmitters, personal fitness and GPS trackers that we use (daily), which we still charge using energy derived from burning fossil fuels. It makes sense to charge these portable devices using energy harvested from small body motions or other renewable sources."[3] The ability to have our garments run our ubiquitous devices could also change the way we communicate and value our clothing.

## GENERAL DEVICE MECHANISM:

Wearable energy harvesting generators are usually designed to scavenge mechanical, solar and thermo energies.

### PIEZOELECTRIC GENERATOR (PENG)

Piezoelectric nanogenerators (PENG) produce electrical energy based on mechanical deformation such as pressing, bending, and stretching. The basic working principal is based on the electric dipole moment or the separation of positive and negative electrical charges within a system that is instigated by the aforementioned mechanical deformations.[4] One of the disadvantages of PENGs in its application to apparel design is that the efficiency of power generation is dependent upon the frequency of the deformation. Due to the erratic nature of body movements throughout an average day, this could limit its usage to categories of products such as outerwear and activewear—that are products more likely to be exposed to ambient forces such as wind vibration and subjected to constant body motion.[4,5]

### TRIBOELECTRIC GENERATOR (TENG)

Much like PENGs, triboelectric nanogenerators (TENGs) also harvest kinetic energy, but the working mechanism differs in the conjunction of both mechanical deformation and electrostatic induction; mechanical deformations include human motion, vibration, wind and water. The electric generation is based on periodic separation and re-contact of opposite triboelectric charges which can be induced by pressing, bending, and sliding motions.[7,8] When two materials carrying opposite charges come into contact due to mechanical agitation, a charge transfer will occur leaving one side positive and the other negative. An electric field in between the materials is generated when they are released or separated. The repetition of this process will continuously produce alternating current signals.[6,7] Much like PENGs, TENGs also depend on consistent mechanical stress in order to maintain a reliable energy source, which limits its application in apparel design.

### PHOTOVOLTAIC GENERATOR

For photovoltaic wearable generators, materials such as dye-sensitized solar cells (DSSC), organic solar cells (OSC) and perovskite solar cells (PSC) are most commonly used. These solar cells are based on light absorption using dye, organic or perovskite materials that generate mobile electron-hole pairs. [7] For example, organic solar cells can rely on a mixture of light-sensitive polymers and fullerene-like compounds to absorb light and set their electric-generating events in motion, whereas perovskite uses perovskite crystal structures and stoichiometry to collect light.[8,9]

One of the limitations of photovoltaic devices is its reliance on the availability of light. The harvestable energy depends on the spectral composition, incident angle, and intensity of light applied on the PV cells. The spectral composition of natural and artificial light differs. Some PV cells such as c-Si cells are, for example, better for harvesting incandescent lighting. In this vein, the choice of solar cells plays a critical role in the effectiveness of the generator. [9]

Generally, direct sunlight yields better result compared with artificial light sources. Since direct sunlight is mostly available outdoors, photovoltaic generators might also best be applied to categories of apparel product such as outerwear.

## THERMOELECTRIC GENERATOR (TEG)

Thermoelectric generators (TEG), when applied as a wearable technology, scavenge thermo energy that is produced based on the difference of body and ambient temperature. Charge carriers diffuse across the temperature gradient, creating a buildup of charge, and this phenomenon is called the Seedback Effect. Two electrical conductors in the TEG generate the electric charge when heat is applied on one of the two semi-conductors, and the heated electrons flow toward the cooler one via electrical circuit forming a thermocouple. Most TEGs are composed of multiple thermocouples to increase efficiency.[10,11] The design configurations of TEGs are usually in-plane or in-depth. Seedback Effect occurs laterally across an in-plane design, induced by temperature difference between two extremities, a cold end and a hot end of the device. On the other hand, in-depth configuration generates energy through the thickness direction of the device. The latter is more appropriate for apparel because the design is more conducive to exploiting the temperature difference between the environment and the body using the garment as the interface where one becomes the cold end and the other the hot end. The greatest, comparative advantage of TEG to other generators is its independence from mechanical motion and the light, both of which are variable sources, making it a relatively more consistent energy generator. On the flip side, TEGs generally yield the least energy output around a few microvolts per kelvin, and the typical difference between the skin and the ambient temperature is 1 kelvin.[11]

## CHALLENGES OF ENERGY HARVESTING DEVICES FOR APPAREL

Energy Harvesting materials have been successfully integrated into accessories such as shoes and backpacks, but there is very little literature on their integration into finished garments.[12] The mechanical challenges of integrating the devices into apparel are not only to ensure robust and stable output but also to ensure the connectivity from harvester to the electronic devices. For example, batteries, capacitors or power management circuits (PCM) are still required for most of the existing energy harvesting materials to help regulate the consistency of electric flow to the end device. This complicates the circuitry and washability of the final garment.

I was able to go to Montreal to interview Joanna Berzowska, associate dean of Fine Arts, and a pioneer in wearable technologies and computation arts, as well as Hexoskin, a company that commercialized smart biometric athleticwear, to learn about the challenges of e-textiles and review samples of connected garments. Although much advancement has been made in converting conductive materials into fiber and ink forms that improve their weight and practical aspects of the finished product, the devices necessary to process information such as biometrics through the embedded fiber sensors are still not immune to laundering, and in most cases have to be removable. This is relevant to energy harvesting materials because one of their main usages is to power electronic devices.

I also attended the Industrial Fabric Association International (IFAI) Advanced Textile Conference in September 2017 that took place in New Orleans. During the conference I was able to gather more information from lectures on energy harvesting materials. In one lecture, associate professor Jesse Jur, from the College of Textiles (TECS) at North Carolina University, discussed challenges and solutions in printed electronics, including energy harvesting materials. Mechanical Engineering professor Chris Rahn, from Penn State University, discussed some of the promising research on the subject and different types of energy harvesting materials.

The conference also offered insights on the smart textile market, in general, such as the potential areas of research opportunities and the infrastructure that still needs to be developed to support the evolution and commercialization of smart textiles. One example is testing and the development of new standards for textiles with embedded electronics.

All of the above provided valuable information to enrich my understanding of energy harvesting materials and the direction of smart textiles development in general.

Thank you, members of the Faculty Development Committee and Academic Affairs Office, for your support on this research.

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## INTERVIEWS

07/06/2017 Professor Jesse Jur, Associate Professor College of Textiles (TECS), North Caroline Univeristy

07/06/2917 Despina Papdopolous, founder of Principal Design, and Adjunct Professor at DSI, MFA Design for Social Innovation at New York University

07/11/2017 Xing Fang, Professor of Chemistry at Chongqing University, China

07/11/2017 Ying-Chih Lai, Assistant Professor Chemical Engineering at National Chung Hsing University, Taiwan

08/29/2017 Dong S. Ha, Viriginia Tech, Professor at The Bradley Department of Electrical and Computer Engineering

## ON-SITE INTERVIEWS AND RESEARCH

06-28-2017 Shugoofta Ahmed, Sales Manager and Kim Neveu, Designer, Hexoskin, Wearable Body Metrics, Montreal Canada

06-28-2017 Joanna Berzowska, Associate Dean of Fine Arts at Concordia University and founder of XS Lab for Design and Computation Art, Montreal Canada

08/11/2017 Melik Demirel, Director of Center of Research on Advanced Fiber Technology (CRAFT), and Professor of Engineering Science and Mechanics at Penn State

09-26 to 09-28, 2017 Industrial Fabric Association International (IFAI) 2017 Advanced Textile Conference, New Orleans, LA