Electronics and
Computer Science

UNIVERSITY OF Southampton

Energy Harvesting for Wearable Applications

Professor Steve Beeby
Department of Electronics and Computer Science
University of Southampton, UK

Energy Harvesting 2017

Overview

- Overview of ECS research
- Background:
  - Wearables applications
    - CREATIF project
    - FETT project
  - Energy harvesting
- Energy Harvesting for Smart and Interactive Textiles (SFIT)
  - Piezoelectric and thermoelectric materials, textile supercap
- SPHERE project
  - Ferroelectret material development and applications
  - Photovoltaics on textiles and hip implant harvester

Southampton and ECS

- University of Southampton one of the top 15 research Universities in the UK
- ECS was founded over 65 years ago
- 106 academic staff (36 professors)
- 140 research fellows, 250 PhD students
- 800 undergraduates and 300 MSc students
- Over 25 years experience in developing microsystems and active materials
- Research funding to date: £6.3 M for energy harvesting £7.8 M for e-textiles
- 9 Research staff, 12 PhD students

£100 million Mountbatten Building,
housing state of the art cleanroom.

Energy Harvesting Research

1995 - First EH proposal submitted

1999 - First EH project funded by EPSRC

1999 - Thick-film piezoelectric generator demonstrated

2000 - First electromagnetic generator

2004 - EU funded VIBES project

2004 - Formed Perpetuum Ltd

2008 - TRIADE (Development of Technology Building Blocks for Structural Health-Monitoring Sensing Devices In Aeronautics)

2010 - Host UK Energy Harvesting Network

2010 – TIBUCON (Self Powered Wireless Sensor Network for HVAC System Energy Improvement)

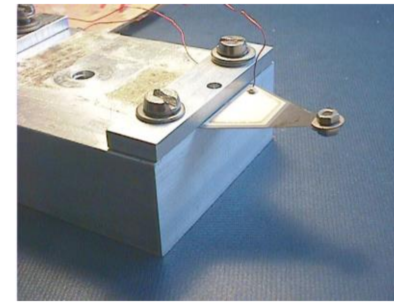
2010 - Energy harvesting on fabrics

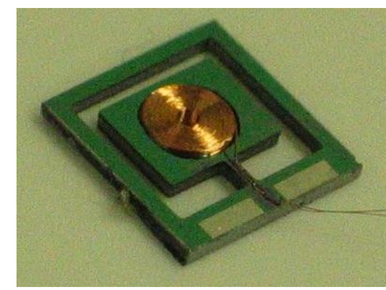
2012 – CEWITT project (EH for smart tags)

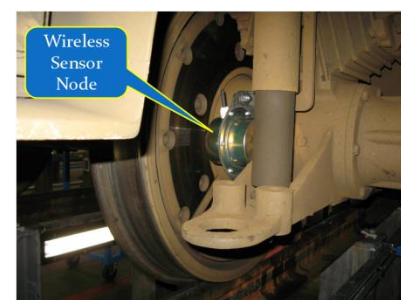
2013 – ENERGYMAN (Long-term energy storage, TSB project with Perpetuum)

2013 – SPHERE project (EH for wearable applications)

2015 – WARNSS Project (with Perpetuum)







e-Textiles Research

2008 - EU FP7: project MICROFLEX (printed MEMS on Textiles)

2010 – EU FP7: project BRAVEHEALTH (printed electrodes on textiles for ECG monitoring)

2010 – EPSRC: Energy Harvesting Materials for Smart Fabrics and Interactive Textiles

2011 – Formed Smart Fabric Inks Ltd

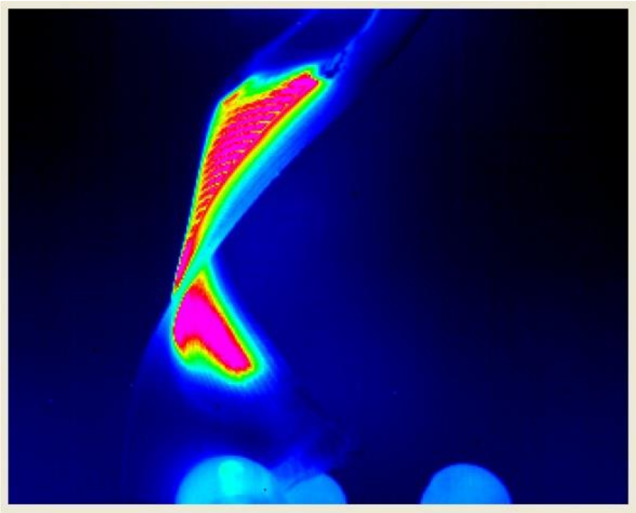
2013 – EU FP7: CREATIF Project (printed functional materials for creative industries

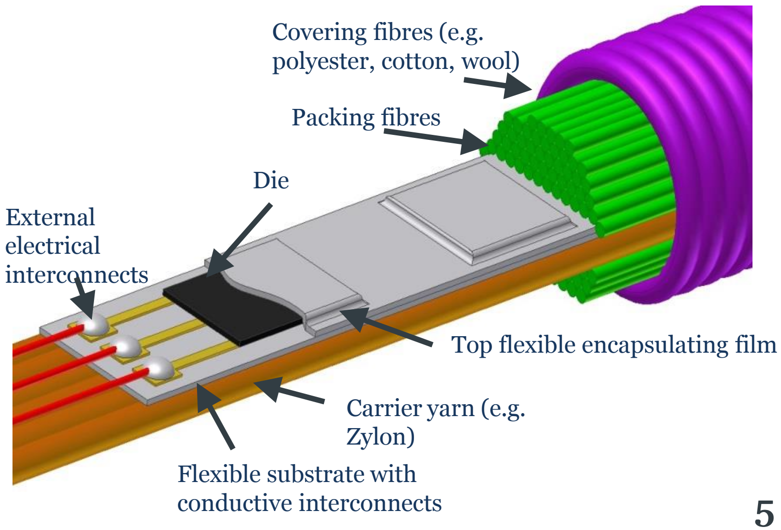
2013 – EPSRC: SPHERE project (EH for wearable applications)

2015 – EPSRC: Novel manufacturing methods for Functional Electronic TexTiles (FETT) (packaging electronics in yarns)

2017 – Dstl: Woven integrated textile sensors for situational awareness and physiological monitoring

2017 – EPSRC:Wearable and Autonomous Computing for Future Smart Cities: A Platform Grant





Background: E-Textile Devices and Fabrication

> "The pure e-textile market will grow from around $100m in 2015 to over $3bn by 2026, with *Sports & Fitness* and *Medical & Healthcare* being the two largest sectors."
>
> \- IDTechEx: E-Textiles: Electronic Textiles 2014 – 2024

Woven fabric circuit board

Printed light emitting textile

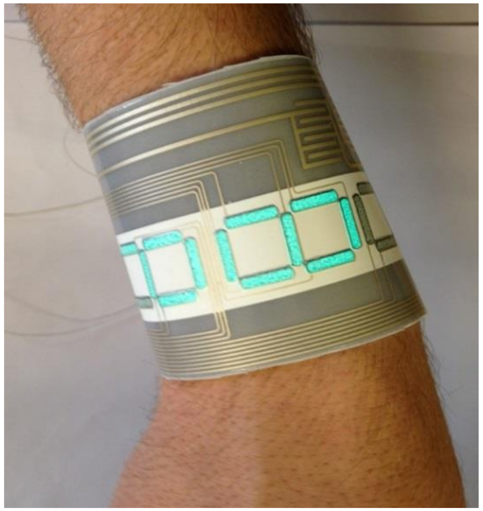
CREATIF Project

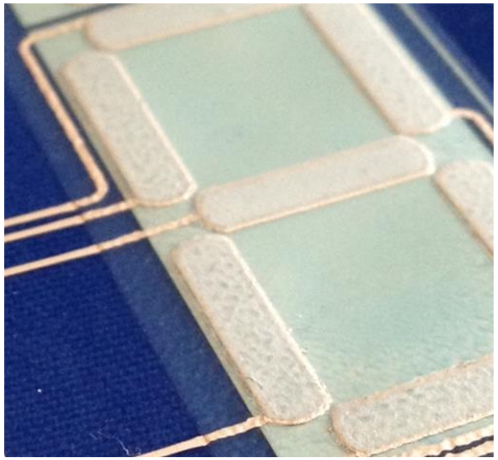
- EU FP7 Collaborative Project – Oct 2013- Jan 2017 – €4.5M – UoS coordinating.
- 7 Partners – 2 Universities, 4 SME's, 1 Large Company.
- Developing a novel dispenser printing system to take the smart fabric design directly on to fabric.
- The software is developed for novice users with little or no electronics experience.
- Software will allow the user to design, create, layout, visualise and simulate smart fabrics before printing them.
- Initial functions are EL lighting, thermochromic colour change, sound generation, touch and proximity sensing.

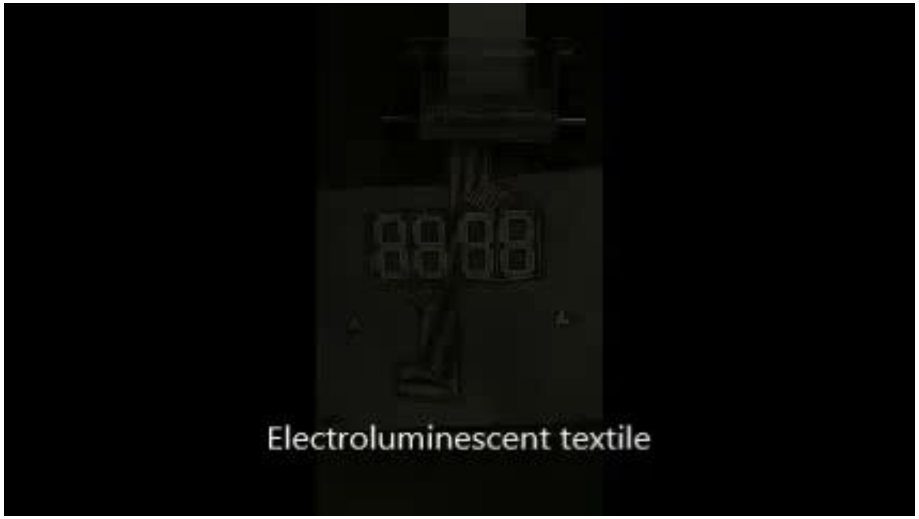
www.creatif.ecs.soton.ac.uk

Screen Printed EL Watch Display

- Low powered lighting, <27 mW when lit.
- Lifetime can be significantly improved through use of touch sensors to turn display on/off when not being read.
- Printed touch switches can be used as a swipe feature to turn on the display.
- Multilayer printing allows compact design.



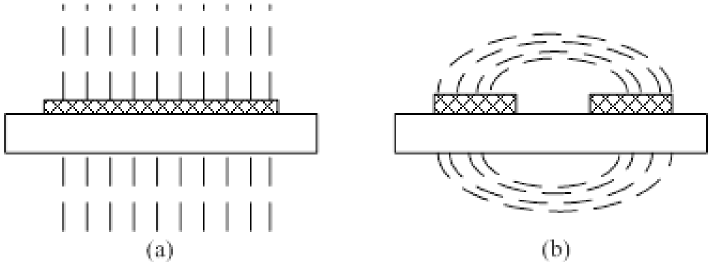




10.1109/JDT.2016.2613906

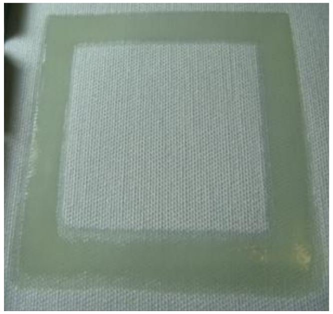
Printed Touch and Proximity Sensor

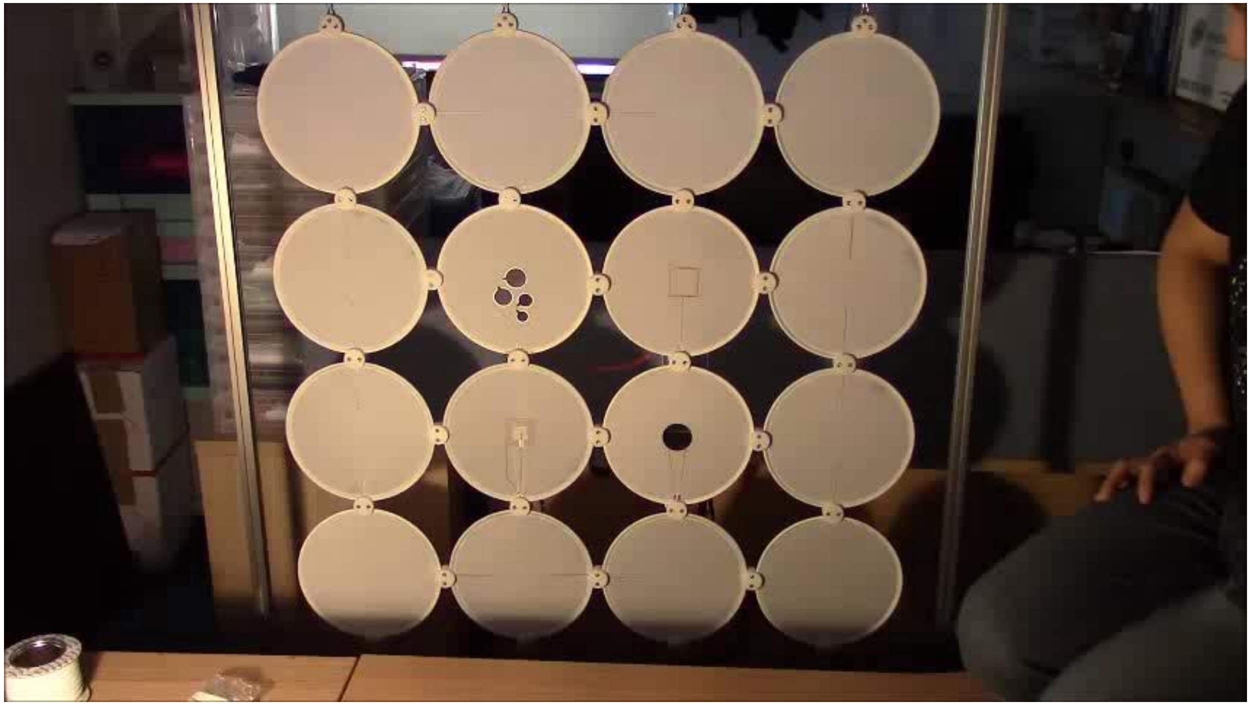
- Principle of operation: change of capacitance between an object and the detector plate.
- Two options can be a single plate with electric field lines directed outwards (a) or two plates with electric field between them (b).



Dispenser Printed Proximity Sensor

- Our study showed that only a detection plate border needs to be printed to function – 10% loss in range but 76% less conductor.
- Video showing the proximity sensor connected with an EL lamp, printed speaker and thermochromic to enable interactive smart fabrics.

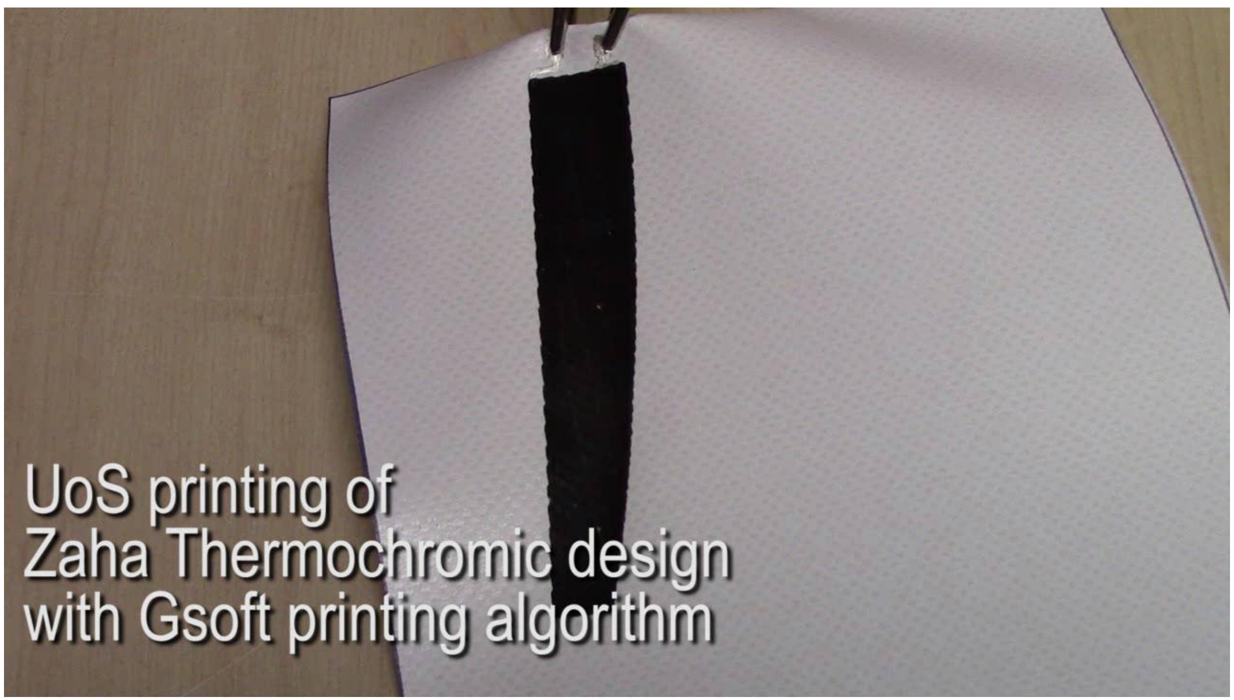




doi:10.1016/j.sna.2016.06.005

Thermochromic Ink

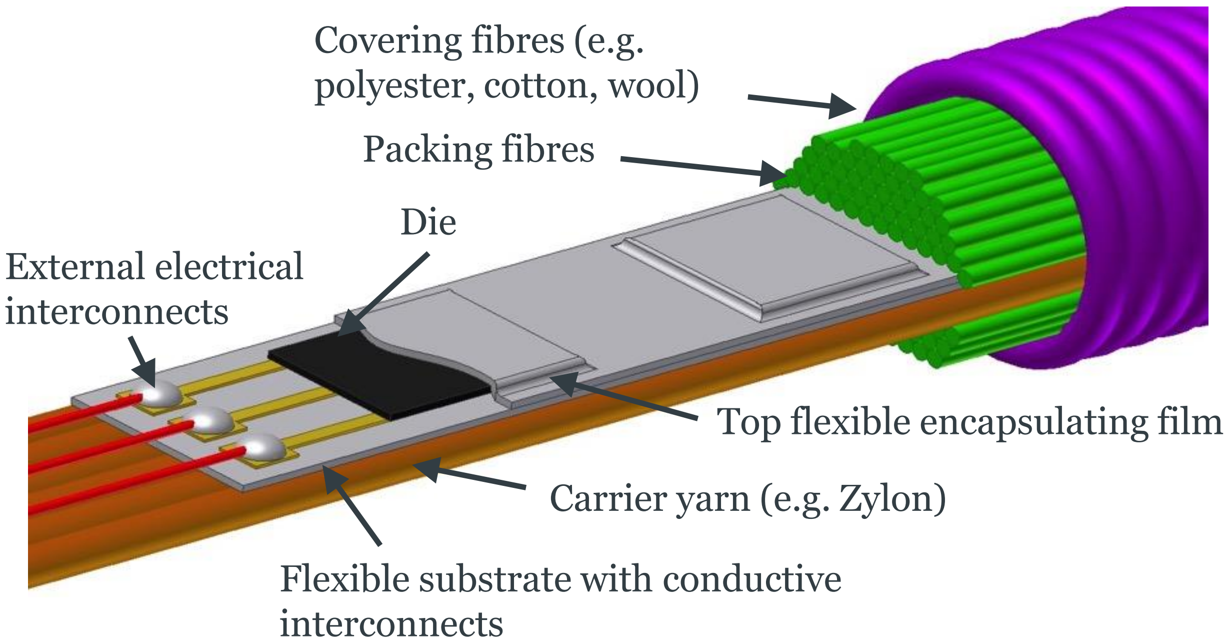
- Coupled to heater – controlled change in textile appearance. Heater layout automatically designed depending upon shape of thermochromic region.



FETT project

£2.8 M Project with Nottingham Trent University.

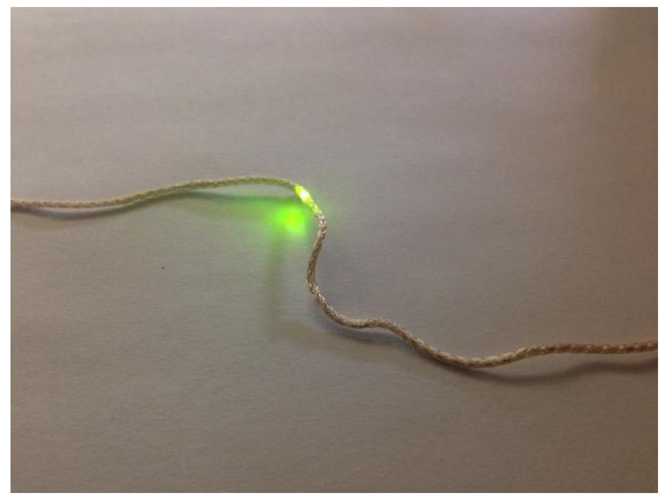
Research and development of new scalable manufacturing and assembly methods that add ***true*** electronic functionality to textiles. Packaging silicon die in yarns using photolithography and etched copper Kapton circuit strips.



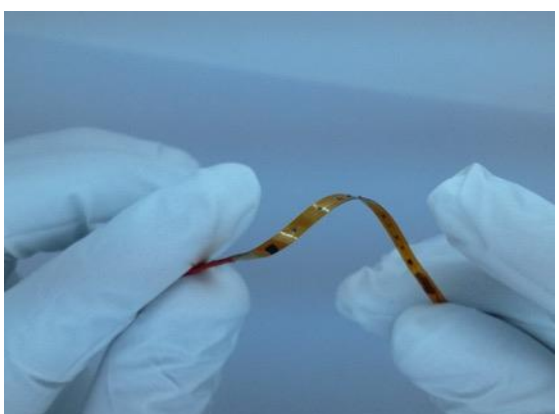
Example circuit

ATtiny20 microcontroller integrated onto a strip circuit, 1.5 mm wide, with sensors and LEDs (all bare die). Strip circuit fabricated into a textile yarn.

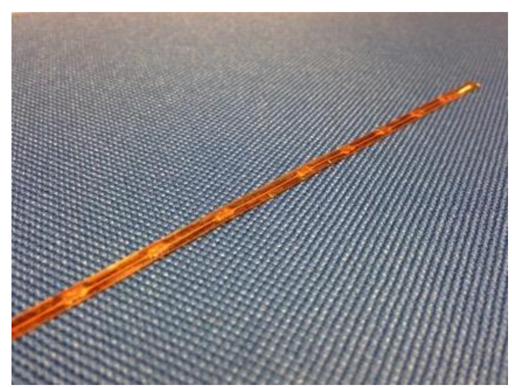
Functioning circuit before forming strip



Circuit fabricated in yarn



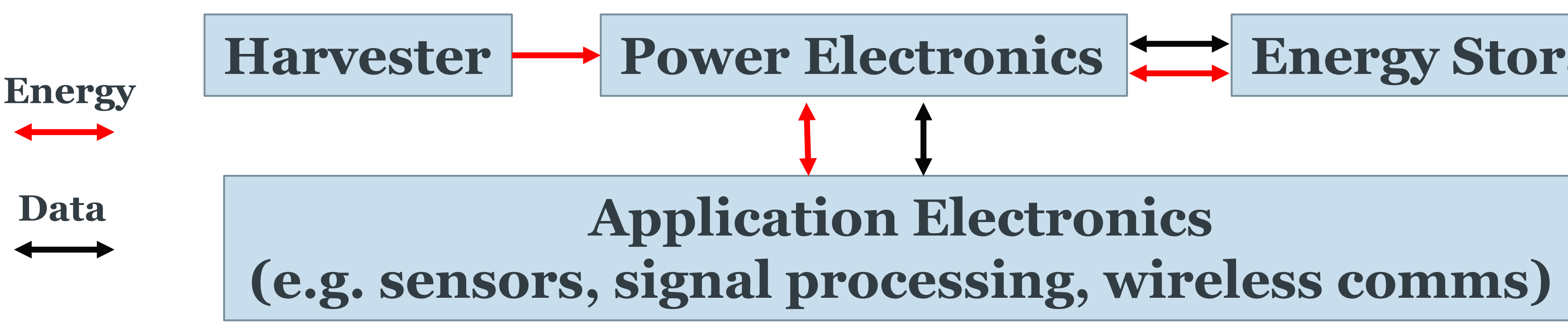
Circuit in strip form



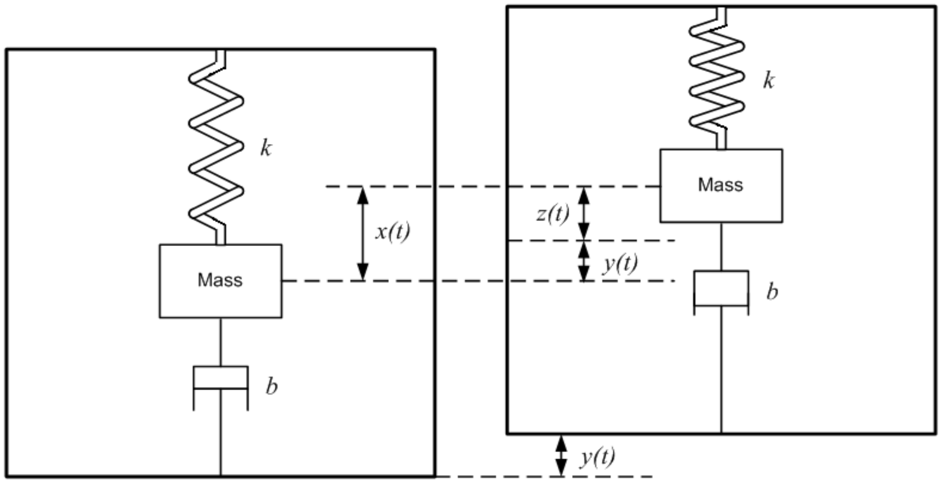
Test circuit with encapsulating moulded Kapton top layer

Background: Energy Harvesting

- Harvesters serve as a localised power supply for wireless devices to replace or augment batteries.
- Many different technologies available for different energy sources.



Capturing Mechanical Energy



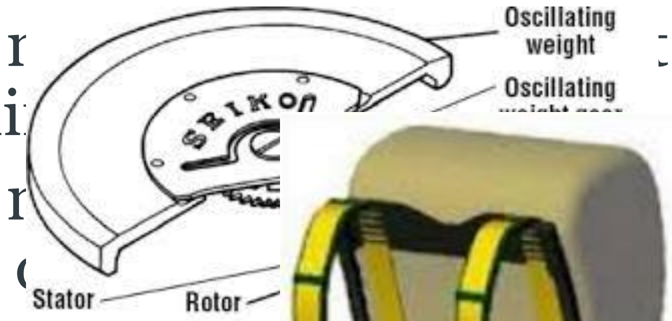
Inertial generator – Mass m, stiffness k, mass displacement $z(t)$, damping coefficient b and input amplitude $y(t)$.

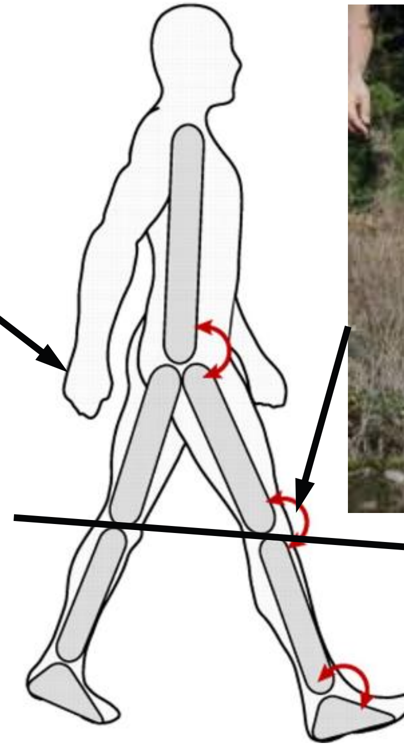
$$\omega_{res} = \sqrt{\frac{k}{m}}$$

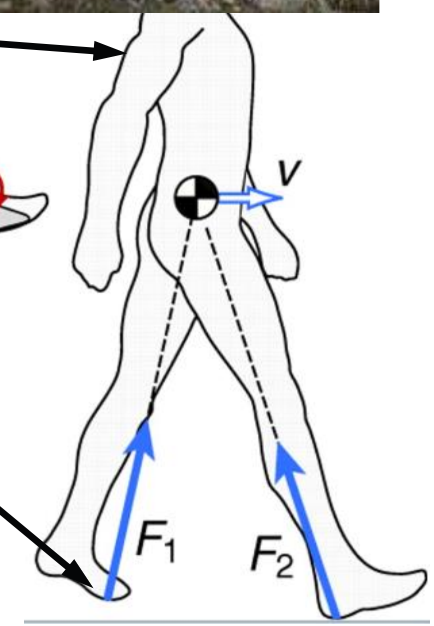
- Majority of generators are inertial devices (not all)
- Mechanical structure resonates at characteristic application frequency
- Design depends upon the nature of the mechanical energy i.e. ***APPLICATION SPECIFIC***

Human Applications

- Human r
  to machi
- Human r
  by large (
  frequencies
- Opportunities for
  mechanical energy
  - Motion
  - Forces
  - Impulses
- Other sources – therm
  solar



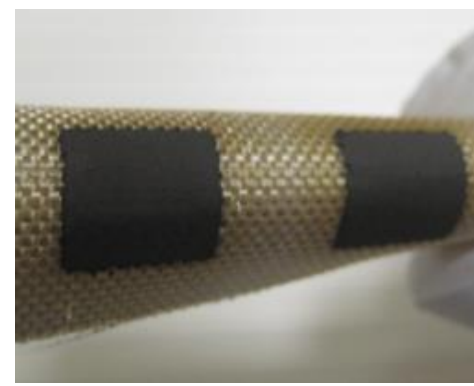




Energy Harvesting Materials for SFIT

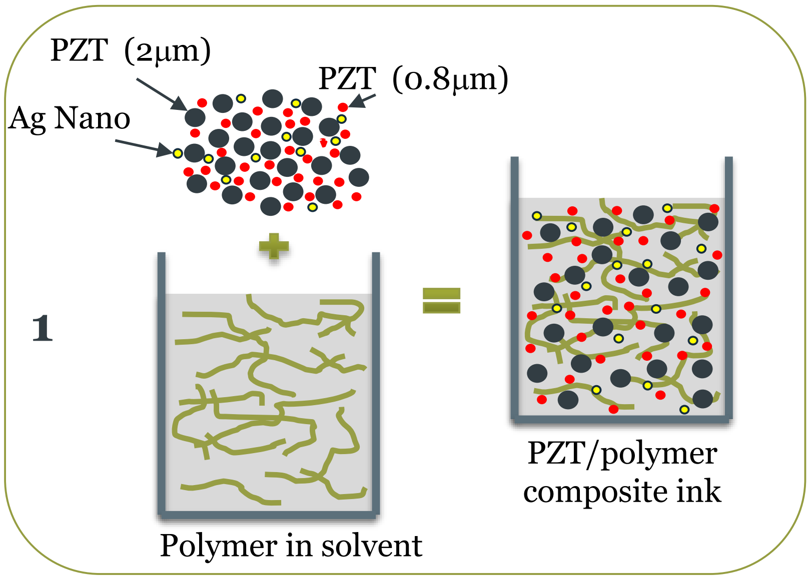
- 5 Year Leadership Fellow scheme
- £1.16M to investigate the integration of energy harvesting functionality in textiles
- Developed piezoelectric and thermoelectric polymer composite inks for application on textiles to harvest energy from mechanical motion and heat
- Investigated textile supercapacitors for storing energy

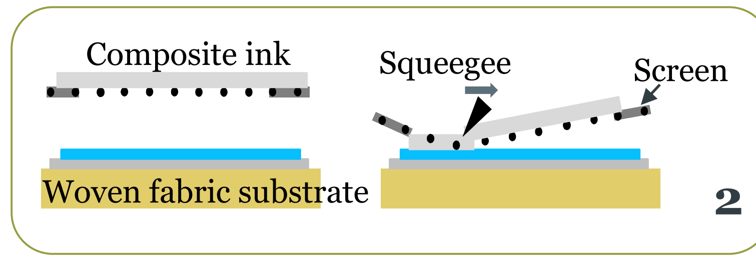
Flexible piezoelectric film

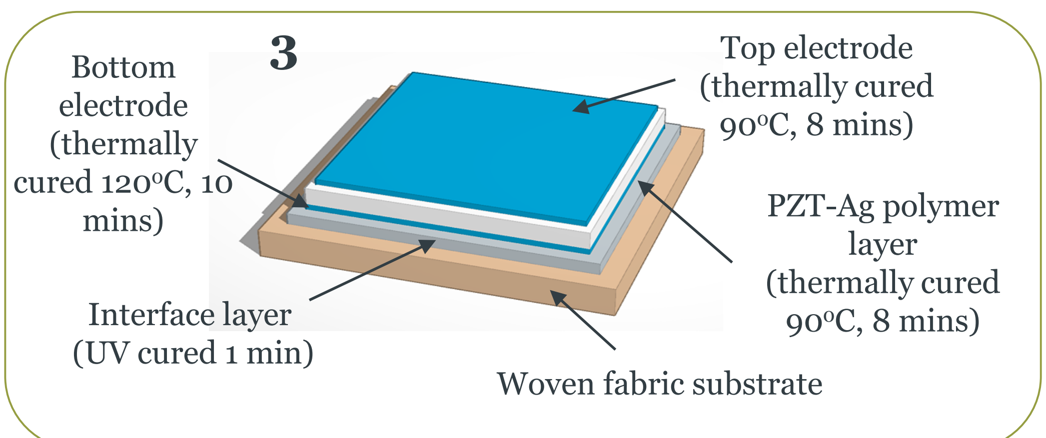


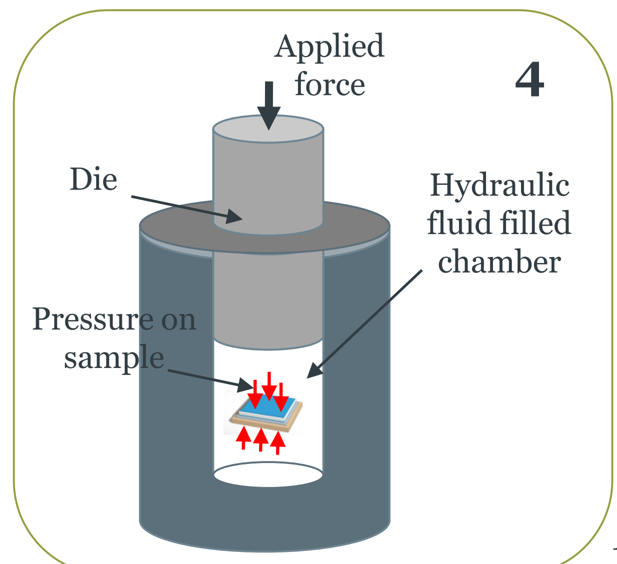
Flexible thermoelectric film

Composite Polymer Piezoelectric Ink





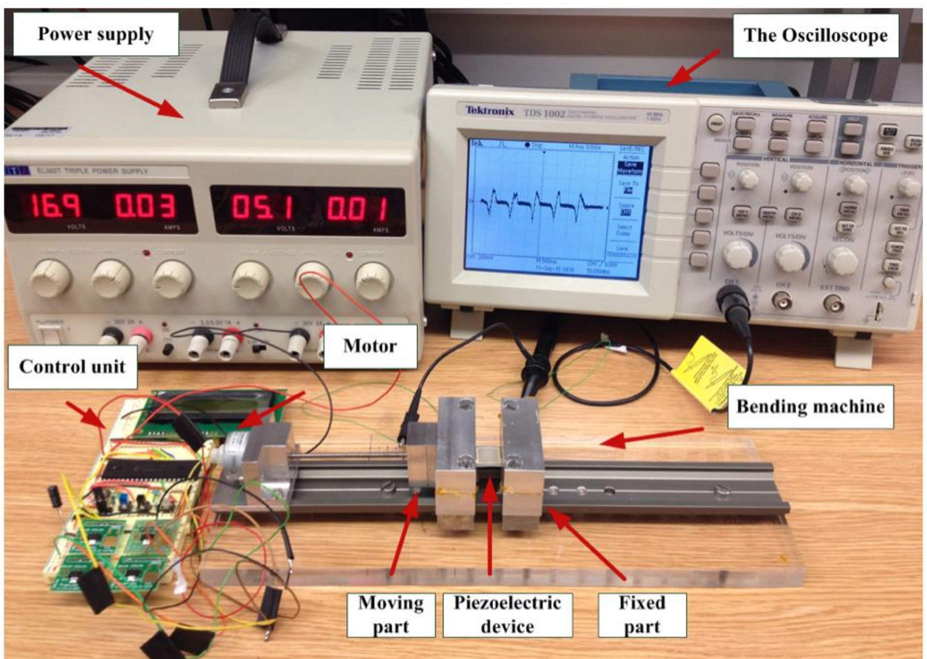


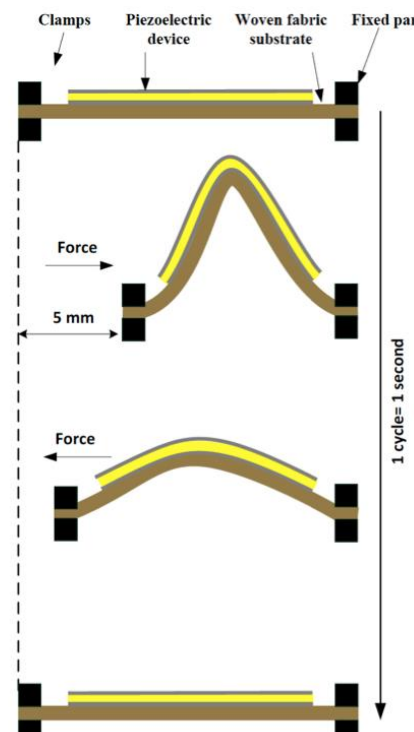


doi:10.1016/j.nanoen.2017.01.037

Piezoelectric Ink Performance

- Piezoelectric activity gauged by freestanding d_{33} coefficient which equals 98 pC/N (PVDF ~ 30pC/N).
- 38 and 14 μJ energy generated per compression and bending action (assuming 10 x 10 cm sample, 100 μm thick)

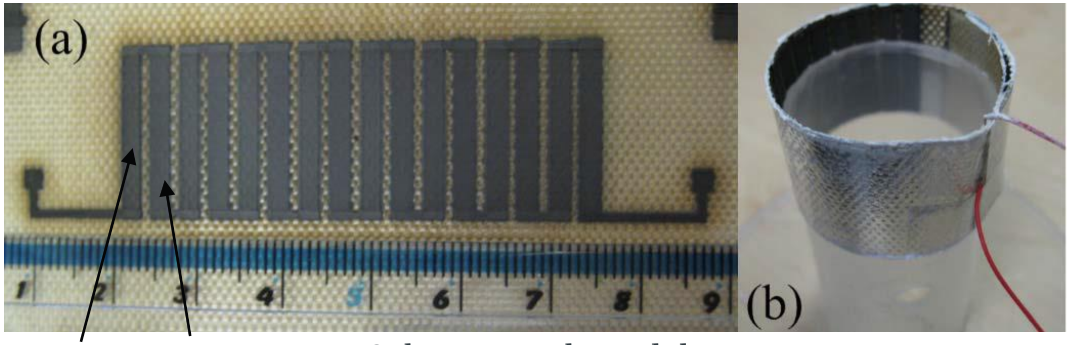




Composite Polymer Thermoelectric Ink

- Bismuth Telluride and Antimony Telluride powders mixed with epoxy based binder. Optimum loading 86%.
- Two inks printed to form series of thermocouples on textile.
- Minimum curing temperature 250 °C.

Material	α (μV/K)	ρ (Ω·cm)	λ (W/(m·K))	Power factor (μW·K^{-2}cm^{-1})	ZT (T=300 K)
$Bi_{1.8}Te_{3.2}$ Thick film	-138.4	9.97×10^{-3}	0.426	1.92	0.135
Sb_2Te_3 Thick film	108.5	3.6×10^{-3}	1.036	3.27	0.095
Bulk n-Bi_2Te_3 [15]	-227	1.4 – 3.8×10^{-3}	1.5–2.5	13.6 – 36.8	0.163 – 0.736
Bulk Sb_2Te_3 [15]	110	2.5 – 6×10^{-4}	2.8–7.3	20.2 – 48.4	0.083 – 0.519

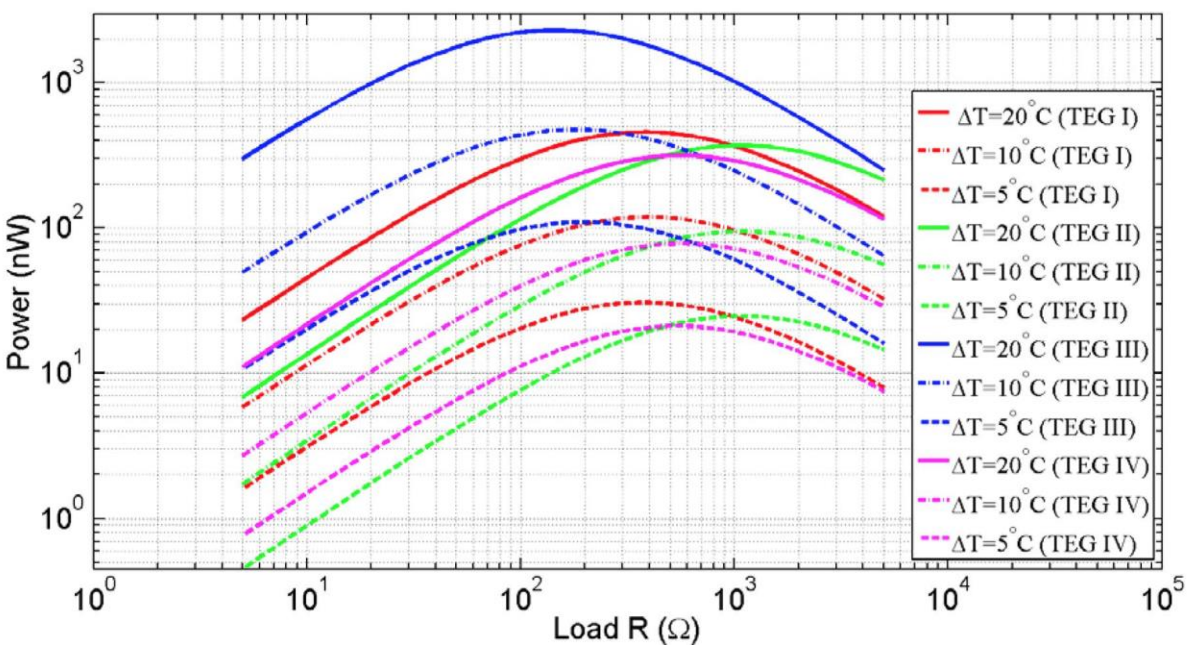


8 thermocouple module

10.1109/TED.2016.2603071

Printed Module Performance

- Series of designs evaluated. TEG III (glass textile substrate, SbTe interconnections, 174 μm thick

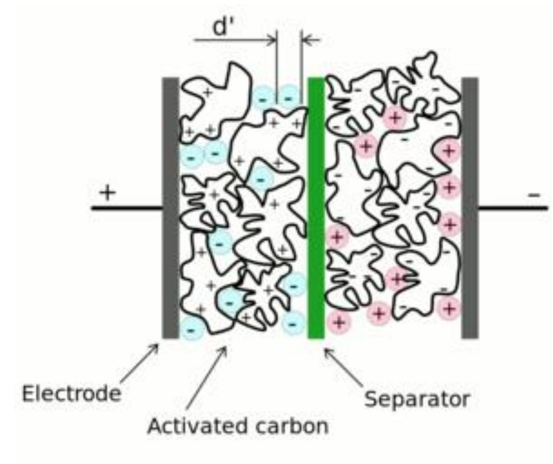


- Max power for a 20 °C temp gradient 2.3 μW.
- Shortcomings: film resistance, flexibility, processing temperature, toxic materials.

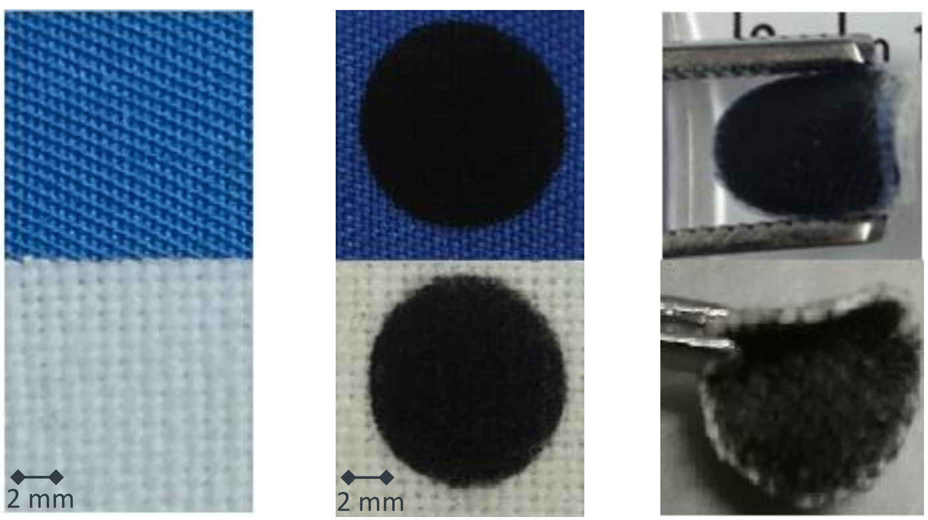
10.1109/TED.2016.2603071

Textile Supercapacitors

- Cotton based supercapacitors fabricated by spray coating low-cost activated carbon ink.
- First every single textile layer device demonstrated.



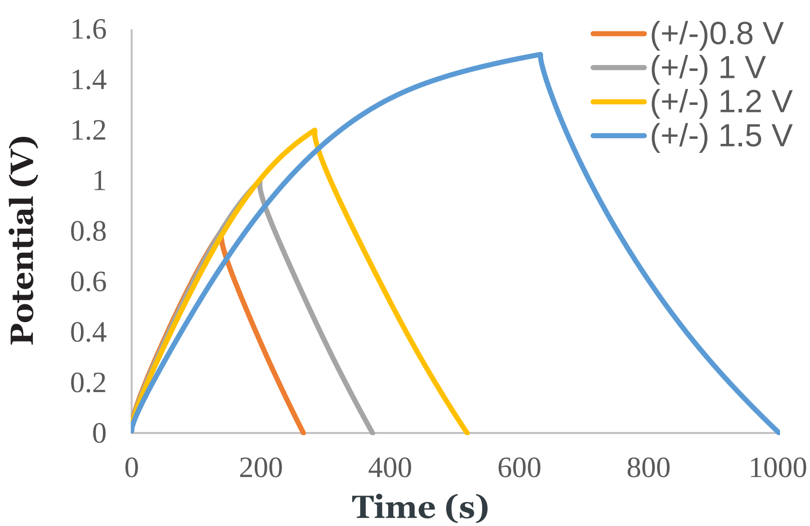
Controlled spraying leaves center of textile uncoated



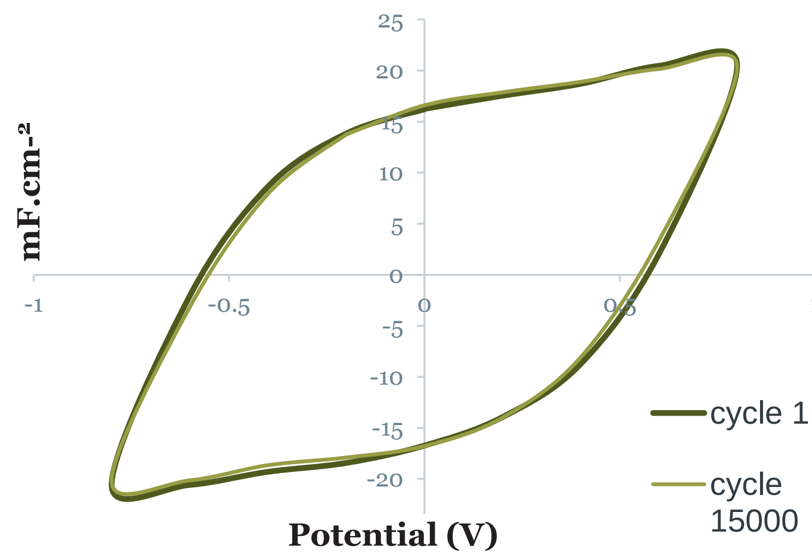
Spray coating → Vacuum impregnation →

Supercapacitor Performance

- The single layer cotton device achieves an area capacitance 49.1 mF.cm^{-2} and power density of 14.2 mW.cm^{-2} when charged up to 1.5 V
- Excellent stability demonstrated up 15,000 cycles

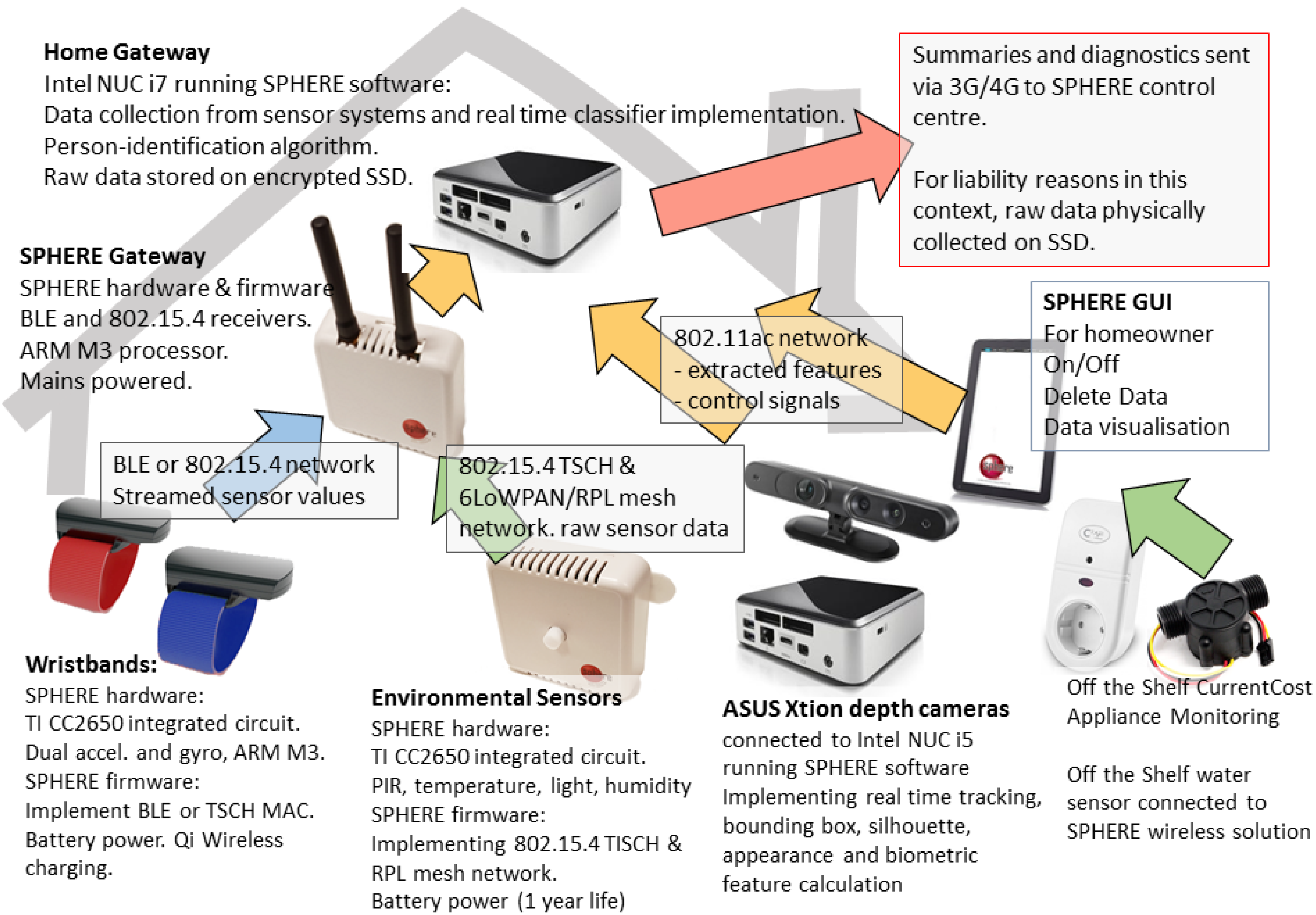


Galvanostatic cycling tests of single layer textile supercapacitor with cotton electrode (0.1 A.g^{-1}) between 0.8 V to 1.5 V



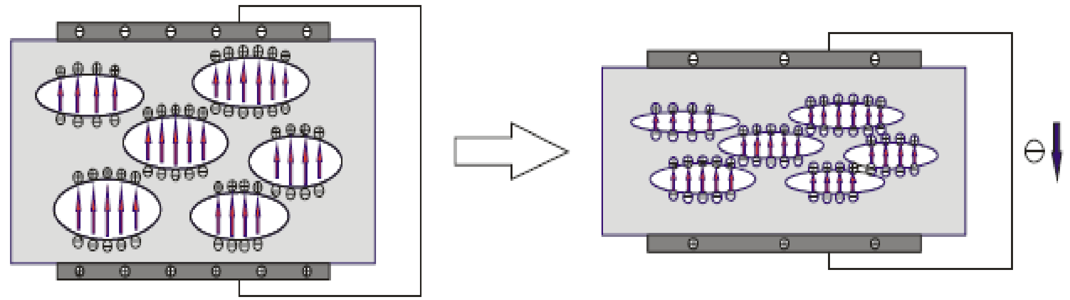
CV test of the cotton solid-state supercapacitor for 1 and 15000 cycles between +/- 0.8 V at a scan rate of 200 mV.s^{-1}

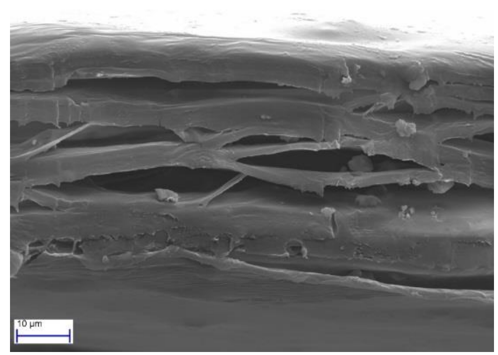
SPHERE Project - £14m IRC project



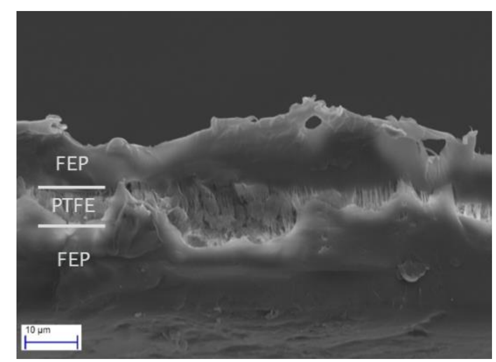
Ferroelectret Materials

Ferroelectret materials contain dipoles due to the surface charge in the voids within the material. Under strain, voids change shape and net charge flow occurs across the material. Typically made from foams – other materials under development. **Highly compliant – good for human applications**.





Polypropylene (PP) ferroelectret (Emfit Ltd)

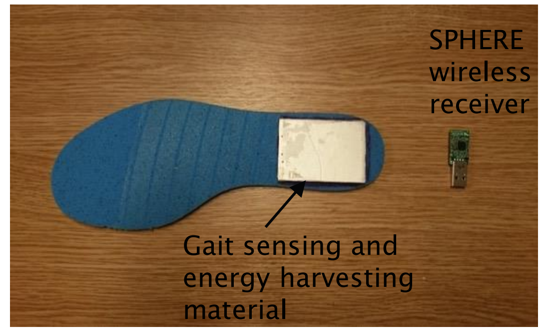


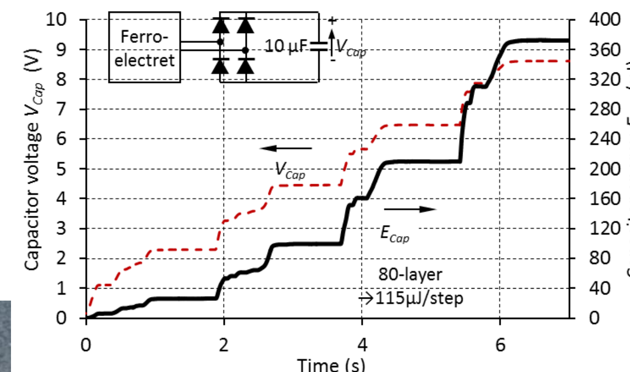
PTFE ferroelectret

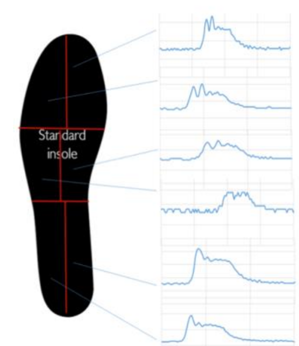
Applications: Insole Sensors for Gait Analysis

Implemented the materials as a combined energy harvester and sensor in a shoe insole:

- Single sensor employed as a self powered pedometer (4% error when walking)
- Wireless transmission powered by footfall used for indoor localization.
- 6 segment insole used for gait analysis. Provides force distribution data. (Not self powered)

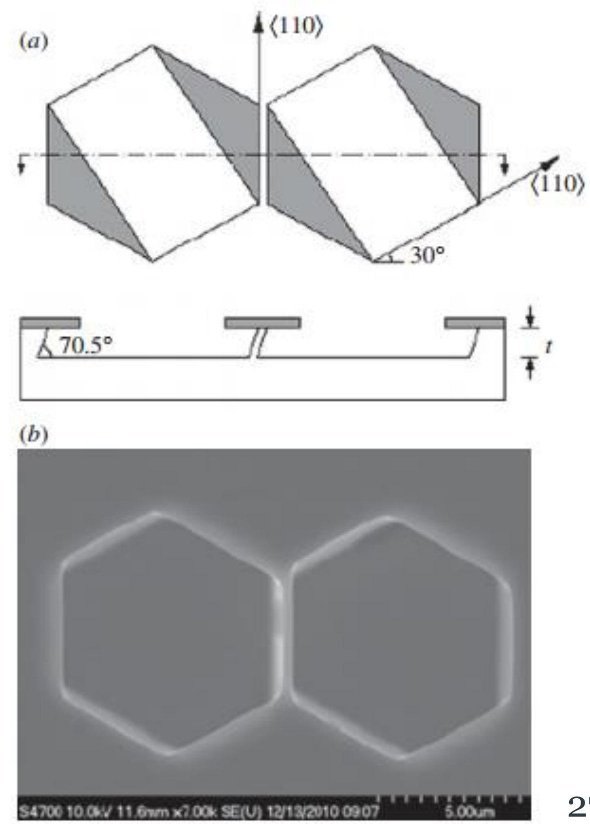


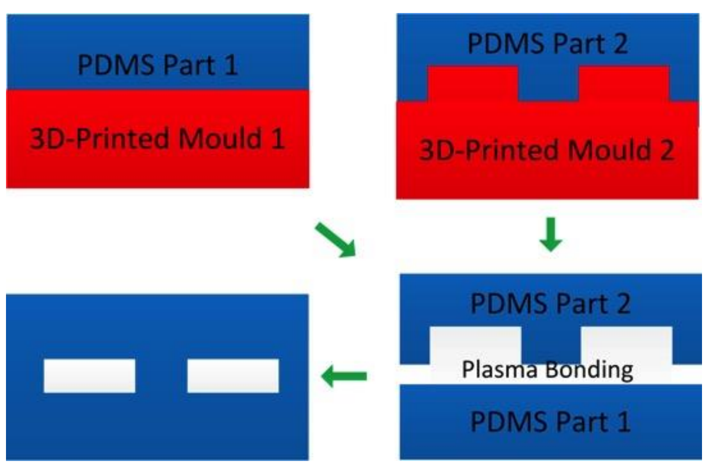




Microengineered Ferroelectret

- Improve ferroelectret response by engineering the void geometry.
- Latest work uses etched silicon mold, <110> wafer gives parallelogram.
- d_{33} readings of 210 pC/N and 300 pC/N for the rectangular and parallelogram voids respectively

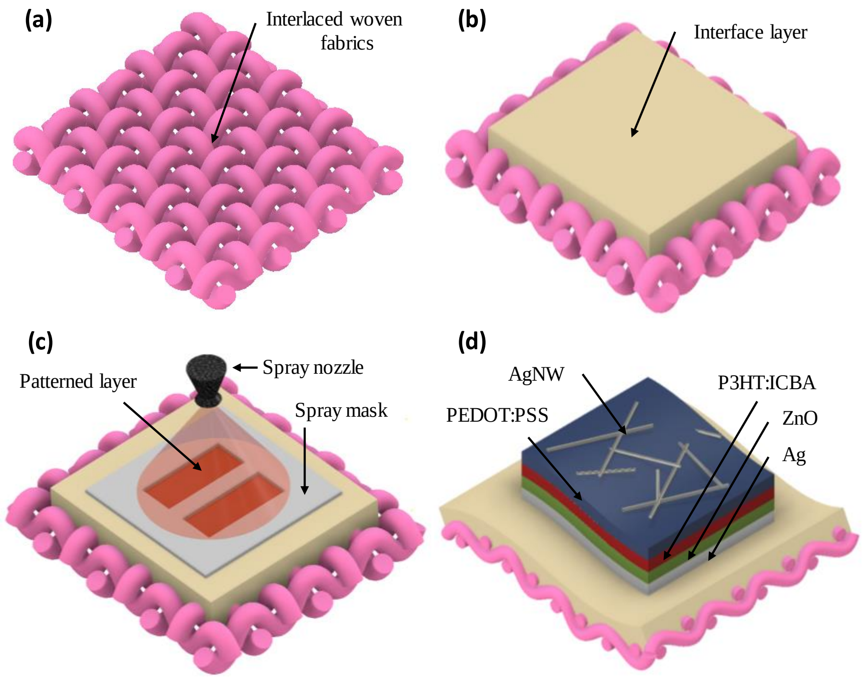


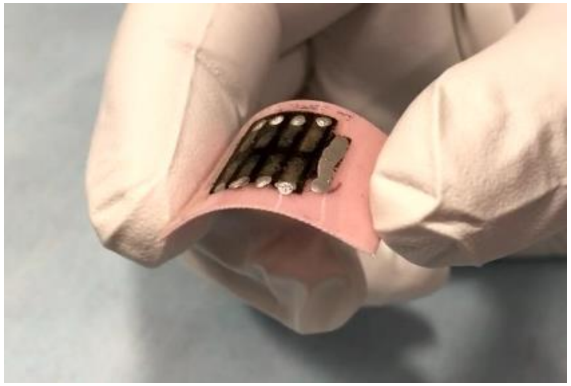


Photovoltaic Textiles

Investigated organic and dye sensitised solar cells fabricated on textiles. The limit on processing temperatures is a real challenge. Use spray coating and doctor blading. Device thickness <1 mm. Efficiency 1.2% achieved.

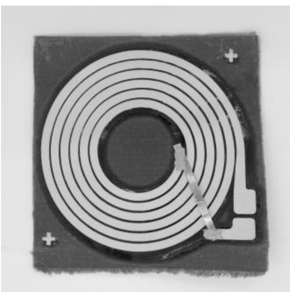
Issues of stability and scalability remain.



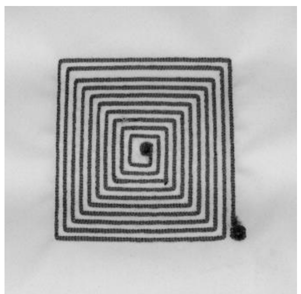


Inductive Power Transfer – Textile Coils

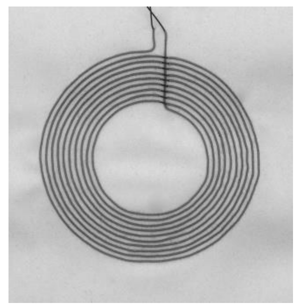
Wireless power transfer is a good option to recharge devices whilst sitting in your favourite chair.



Printed



Embroidered



Overstitched

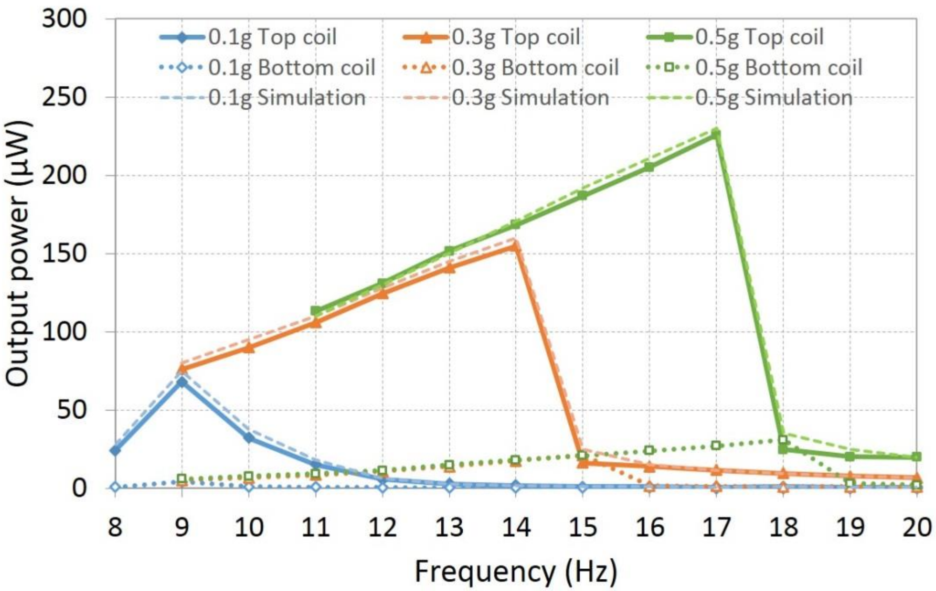
We have investigated different types of textile coils for use in inductive power transfer applications.

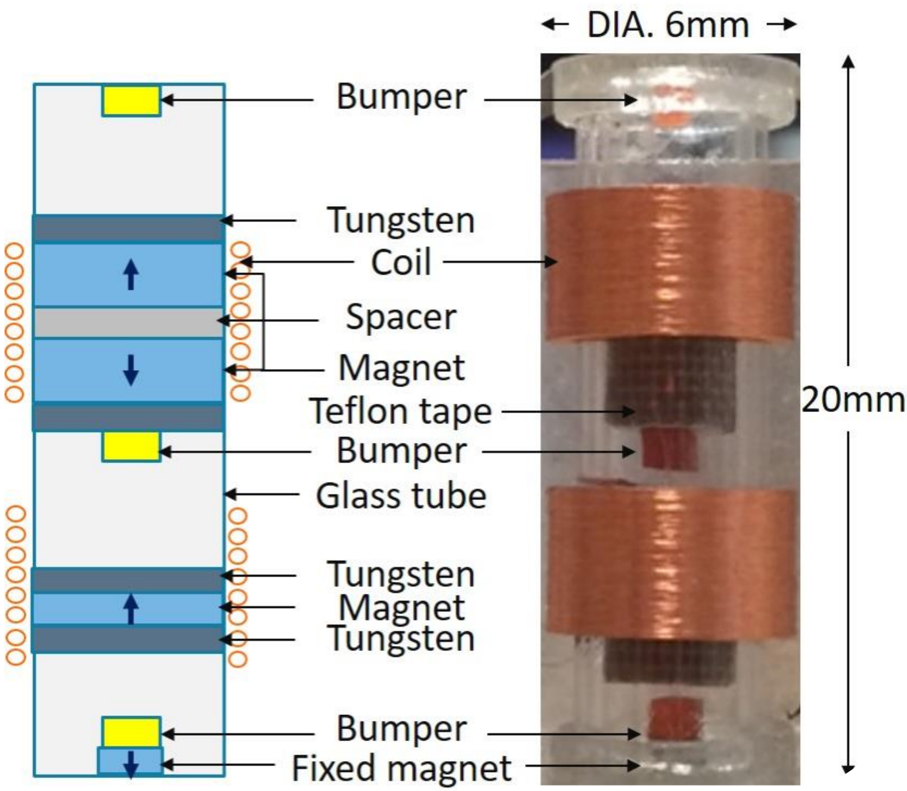
Flexible textile implementations suffer higher track resistances and limited coil turns. The Q-factors of the printed, embroidered and overstitched coils is 3.6, 1.3 and 18.3 respectively. Overstitching is certainly the preferred option.

Embedded conductive yarns for wireless power transfer. Enables enough power to charge a mobile phone.

Energy Harvester for a Hip Prosthesis

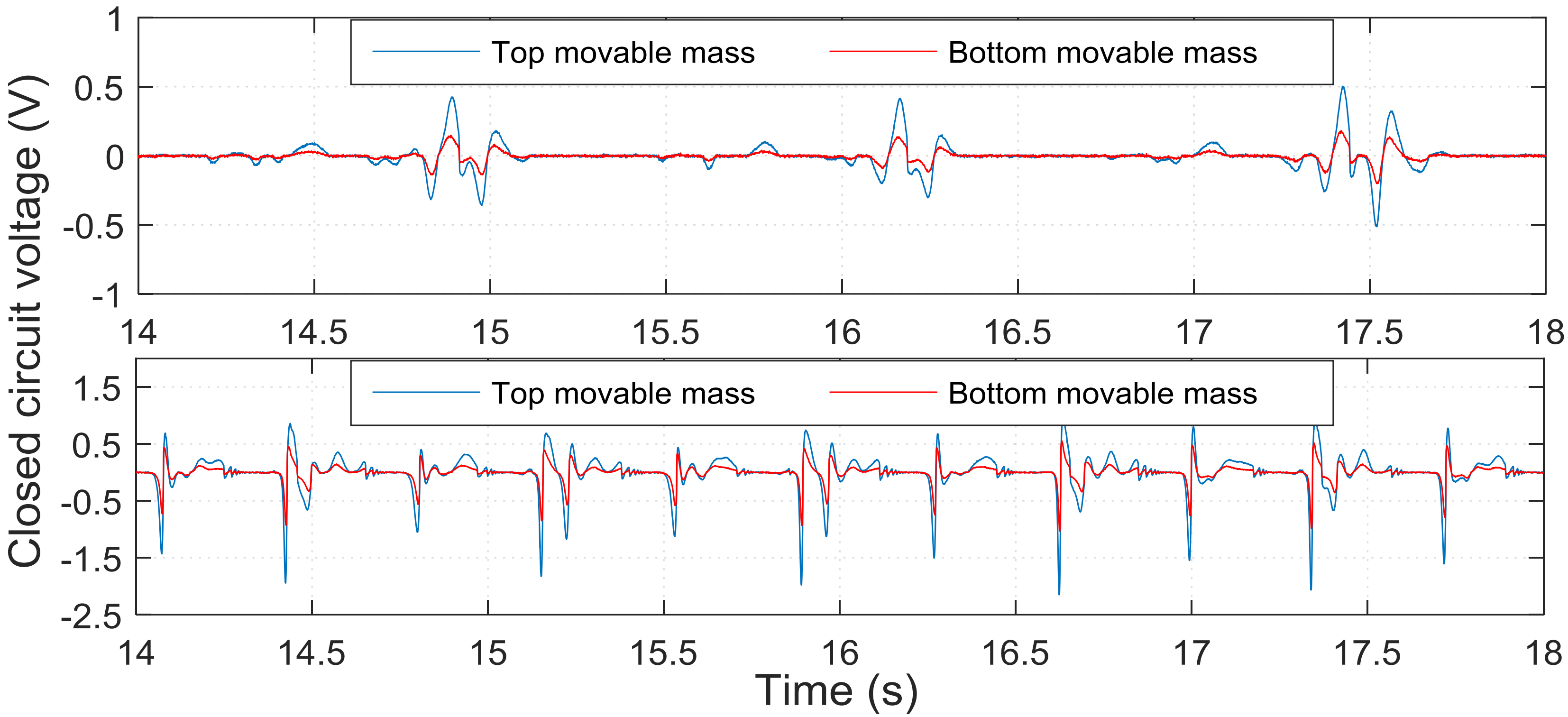
Instrumented hip prosthesis require external recharging or built in energy harvester. Investigated small size, low frequency EM harvesters.





Hip Harvester Results

Harvester mounted at hip whist used walked/jogged on treadmill.
Useful output power (~6 and 37 μW respectively) but voltage low.



Conclusions

- There is certainly demand for energy harvesting in wearable devices.
- Energy harvesting in such human based applications very challenging.
- Textile implementations provide a universal platform but place constraints on materials processing.
- Textiles do not couple mechanical energy effectively to active printed materials.
- Engineered ferroelectret materials show good promise and could negate the poor textile coupling.
- Practical thermoelectric harvesting from humans problematic.
- Solar harvesting from textiles technically challenging but many potential applications.
- Wireless power transfer coupled with energy storage a viable approach.

Acknowledgements

- John Tudor, Russel Torah, Kai Yang, Neil Grabham, Yang Wei, Abiodun Komolafe, Sasikumar Arumagam, Yi Li, Jerry Luo, Sheng Yong, Zhou Cao, Dibin Zhu, Olivia Ojuroye, Menlong Li, Jingqi Liu, Marc de Vos, Ahmed Almusallam, Gordon Paul, Zeeshan Ahmed, Chris Freeman.

- Funding bodies: Engineering and Physical Sciences Research Council (EPSRC), EU Framework 7, Medical Research Council, Dstl

EPSRC

SEVENTH FRAMEWORK PROGRAMME

[dstl]

THANK YOU FOR YOUR ATTENTION!