Institution: University of Southampton

Unit of Assessment: 13 Electrical and Electronic Engineering, Metallurgy and Materials.

Title of case study: 13-05 Good Vibrations: Advancing the Cause of Energy Harvesting

1. Summary of the impact

The University of Southampton's pioneering research into energy harvesting has produced proven economic impacts together with impacts on public policy and international standards. Perpetuum, a spin-out from Southampton employing 10 people locally, has attracted £9.6 million in venture capital and developed the world's leading vibration energy harvester. Perpetuum's harvesters are enabling the deployment of zero maintenance, battery-free wireless systems in the rail industry where the technology has revolutionised bearing monitoring. This has enabled, for the first time, real-time monitoring of rolling stock, leading to cost savings, improved reliability, efficiency and safety. Their systems have been deployed on 200 trains across the UK (Southeastern) and Sweden (SJ AB). Southampton's research has driven wider industrial uptake of the technology and Perpetuum's is also the ***only*** energy harvester approved for use with the worlds leading suppliers of wireless condition monitoring equipment (GE Bentley Nevada, National Instruments and Emerson). Promotion of the technology has led to a £1.25 million TSB competition on energy harvesting and Southampton researchers are assisting in the development of international standards and increasing public awareness of the technology.

2. Underpinning research

Energy harvesting is the conversion of freely available ambient energy (e.g. vibrations) into electrical power to supply low-power, autonomous, electronic systems such as the wireless sensor networks (WSNs) commonly used in the energy, transport, aeronautical and military sectors. Energy harvesters can replace batteries in wireless devices which reduces the maintenance costs incurred in replacing batteries. It provides a flexible 'fix and forget' solution that enables wireless sensors to be placed in inaccessible/hazardous locations since access is not required. Market studies predict the market for energy harvesters will be worth over US$1.9 billion by 2017 [3.1].

The University of Southampton is internationally recognised as a centre of excellence in the development of energy harvesting devices. The underpinning research began in 1999 with a £200k *Self-Powered Microsystems* project [G1] led by White, which produced the world's first piezoelectric vibration energy harvester [3.2] and high efficiency electromagnetic energy harvesters [3.3]. The research placed Southampton at the forefront of vibration energy harvesting research internationally.

Beeby and Tudor then co-ordinated a €4m EU FP6 project, *Vibration Energy Scavenging* (EU FP6 Strep project 507911), which focused on the development of microscale vibration energy harvesting devices. The results published between 2005 and 2008 were among the first worldwide to demonstrate a piezoelectric Micro-Electro-Mechanical System (MEMS) harvester and a miniature electromagnetic harvester with the highest energy density reported to date [3.4].

A spin-out company, Perpetuum Ltd, was formed in June 2004. The founders – Beeby, Tudor, White and Harris – patented the technology and raised over £250k in seed-corn funding. Vital to the company's successful formation was industrially funded research that the Southampton team carried out in 2003 as a subcontractor for US company RLW Inc. [G2]. This work was funded by the US Office of Naval Research and enabled the use of vibration energy harvesting for powering the wireless condition monitoring of fire fighting equipment aboard US naval vessels. This work led the way in the practical application of the technology in real industrial applications and these links carried over to Perpetuum.

The team wrote the benchmark review paper on energy harvesting for microsystem applications [3.5] and they remain at the forefront of energy harvesting research worldwide. Beeby and Merrett lead the UK's Energy Harvesting Network [G3] which includes the UK's leading industrial and academic groups. The network has defined key research challenges and has driven the development of the technology by industry, for example, through the provision of real vibration data enabling the community to develop the technology for real world applications [3.6]. The industrial relevance of Southampton's research was further highlighted by their work in the TRIADE project.

In conjunction with major aerospace companies, EADS, AugustaWestland, Dassault and Eurocopter, this project explored the use of vibration energy harvesting for powering embedded wireless sensors in aircraft and included [G4]. Beeby was awarded an EPSRC Leadership Fellowship on the topic of energy harvesting in 2010 [G5].

Key Researchers (all at the University of Southampton unless otherwise stated)

Prof. Steve P. Beeby (1992 – present), Prof. Neil M. White (1987 – present), Dr Nicholas R. Harris (Senior Lecturer, 1991 – present), Dr M. John Tudor (Principal Research Fellow, 2001 – present), Prof. Bashir M. Al-Hashimi (2004 - present, Dr Geoff Merrett (Lecturer, 2008 – present), Dr Russel N. Torah (Senior Research Fellow, 2006 – present), Dr Peter Glynne-Jones (Senior Research Fellow, 2008 – present), Dr Dibin Zhu (Research Fellow, 2009 – present), Ivo N. Ayala Garcia (PhD student 2008 – 2012, Research fellow at Technological University of Querétaro since 2012).

3. References to the research (the best 3 outputs illustrating quality of work are starred)

[3.1] Markets and Markets report "Energy Harvesting Market- Global Forecast and Analysis (2012-2017) By Technology, Application & Geography", http://www.marketsandmarkets.com/Market-Reports/energy-harvesting-market-734.html (accessed 03/06/2013)

*****[3.2] Glynne-Jones, P., Beeby, S.P., and White, N.M. "Towards a piezoelectric vibration-powered microgenerator." *Science, Measurement and Technology, IEE Proceedings*-. Vol. 148. No. 2. IET, 2001. *(274 citations)*

*****[3.3] El-Hami, M., et al. "Design and fabrication of a new vibration-based electromechanical power generator." *Sensors and Actuators A: Physical* 92.1 (2001): 335-342. *(241 citations).*

*****[3.4] Beeby, S.P., et al. "A micro electromagnetic generator for vibration energy harvesting." *Journal of Micromechanics and Microengineering* 17.7 (2007): 1257. *(331 Citations).*

[3.5] Beeby, S.P., M.J. Tudor, and N.M. White. "Energy harvesting vibration sources for microsystems applications." *Measurement science and technology* 17.12 (2006): R175. *(949 Citations).*

[3.6] Beeby, S.P., et al. "A comparison of power output from linear and non-linear kinetic energy harvesters using real vibration data." *Smart Materials and Structures* 22.7 (2013).

Grants

[G1] 'Self Powered Microsystem', EPSRC GR/M35086/01, £203,559

[G2] 'Advanced Energy Scavenging System for Condition-Based Maintenance'

US Office of Naval Research Phase 2 Small Business Innovation Research project contract N00014-01-M-0151, 28/2/2003 to 12/8/2005.

[G3] 'Energy Harvesting Network', EPSRC EP/H013458/1, 01/03/10 – 28/02/13, £112k (Network continues in a self-funded model). Vibration database: http://eh-network.org/data/index.php.

[G4] TRIADE project, EU FP 7 Strep project 212859, 1/12/08 – 31/12/12, €5.6m.

[G5] 'Energy Harvesting Materials for Smart Fabrics and Interactive Textiles', EPSRC EP/I005323/1, 1/10/10 – 30/9/15, £1.16m.

4. Details of the impact

Research into energy harvesting at Southampton has spearheaded the development of a multi-million-pound industry and enabled the large-scale deployment of wireless sensors in industry and the rail network. Further impacts include the development of international standards, influencing the decisions of funding bodies and raising the profile of energy harvesting among industry and the wider public.

The research was commercialised in 2004 following the launch of spin-out company Perpetuum Ltd [5.1] and has since attracted £9.6m in venture capital. Based at Chilworth Science Park, Southampton, Perpetuum has employed at least 10 people throughout the REF impact period and, with its intellectual property protected by 12 patents, has engineered and manufactured the world's leading practical electromagnetic vibration harvesting microgenerator. The founding academics continue to work closely with Perpetuum in several areas, including a joint TSB funded project to investigate long-term reliable energy storage [5.2].

Economic Impacts

Perpetuum's energy harvesting technology has been adopted by the rail and petrochemical industries where the systems they enable have led to improved business performance through reduced costs, increased efficiency and safety.

Rail Applications: Perpetuum's energy harvesting technology has been adopted by the rail industry where it has enabled **for the first time** the real time monitoring of bearings on rolling stock. **The system is a maintenance free, retrofittable solution that has revolutionised bearing condition monitoring on trains**. Before this, bearings could only be inspected during infrequent manual maintenance checks, which was inadequate, time consuming and expensive. Perpetuum's wireless sensor system is powered by a vibration energy harvester designed to work with the high amplitude, low-frequency vibrations found in rail applications. Perpetuum's sensor nodes monitor individual bearing health and the data is collected centrally on the train and transmitted via GSM to a data centre. A simple summary of fleet condition is available live on the web, with alerts being sent via email or SMS. The system has been developed in partnership with the train manufacturer (Bombardier) and train operator (Southeastern). **The system has been recently exported and has been deployed on 200 trains in the UK and Sweden (SJ AB)** [5.1, 5.3]. The system is currently being modified to also detect 'out of round' wheels (e.g. flat spots) which, if not fixed, can cause excessive impacts on the rails damaging the network and even leading to derailment [5.4]. **In summary, Perpetuum's energy harvesters have enabled wireless condition monitoring that are transforming condition monitoring in the rail industry leading to improved rail safety and reduced maintenance costs**. The cost savings equate to a payback on each installation of less than one year and the lifetime of the system is 25 years [5.1].

Industrial Applications: Wireless condition monitoring is also transforming condition monitoring of machinery in industry that, until recently, was typically performed periodically by an engineer using handheld equipment. **Energy harvesting enables the condition monitoring sensors to be powered by the very vibrations they are monitoring**. Perpetuum's generators are the **only** approved energy harvesters that can be used with General Electric's Essential Insight™ Wireless Condition Monitoring product range [5.5]. GE Bentley Nevada is the world's leading supplier of wireless condition monitoring equipment to the oil/gas and power generation industries. **Perpetuum's generators are fully ATEX-certified for use in hazardous explosive environments**, and the wireless systems they enable can be found in condition monitoring equipment across North America and Europe. For example, in 2008 Perpetuum's generators were deployed in Shell's Ormen Lange gas field in Norway, with **Shell reporting that the self-powered wireless technology has made the utilisation of resources more efficient, reduced the severity of mechanical failures, lowered installation costs and provided more frequent and higher-quality data** [5.6]. Perpetuum's vibration-powered generator is also the only harvester offered by other wireless sensor network manufacturers such as Emerson and National Instruments in their platforms for industrial process measurement, control and condition monitoring applications [5.7, 5.8].

Impact on Public Policy and Society

Southampton's research and influence has raised the profile of energy harvesting and impacted on policy debates relating to research funding calls. Beeby is leading the UK's Energy Harvesting Network, a £112k initiative to connect academia with industrial end-users (list available in [5.9]). As part of the network's activity, three workshops have been held focused on particular application areas (human, built environment and MEMS implementations). Each workshop was attended by industry (including Philips, Rolls Royce, Smith and Nephew, TRW Conekt and NPL) and has led to the publication of a roadmap of the research challenges and future uses of energy harvesting technology. These roadmaps were circulated and discussed with funding agencies and the momentum generated by the Network led to a further workshop, *Energy Harvesting Technology – Creating a New Industry in the UK*, organised by the Technology Strategy Board (TSB) in September 2011. Following this, the TSB opened an Energy Harvesting themed competition in October 2012 with a budget of £1.25m [5.10].

The TSB also fund the Energy Harvesting Special Interest Group (EH-SIG). Prof. Beeby and Roy Freeland (Perpetuum President) [5.1] are members of the steering board which advises the EH-

SIG on its activities which include, for example, trade missions to Germany, Japan and USA promoting UK energy harvesting companies, products and expertise. Further engagement with industry came through the three Energy Harvesting profile-raising events in London organised by Prof. Beeby through the Network, which have attracted over 90 attendees from industry (e.g. Cosworth, Morgan Electro Ceramics, Meggit PLC). Feedback from the industrialists (gathered via feedback forms) was very positive, with 84% rating the events as good or excellent. More general public engagement activities include broadcast media coverage on BBC Radio 4's *Frontiers: Energy Harvesting* [5.11] and *Costing the Earth* [5.12] and Radio Solent news shows. Dr Merrett also participated at the Cheltenham Science Festival where he demonstrated the benefits of energy harvesting to 100 members of the public [5.13].

Impact on International Standards

Prof. Beeby and Roy Freeland (chair) and are assisting in the development of international standards for energy harvesting in an ISA100.18 Power Sources Working Group [5.14]. The group is preparing standards and information documents on power sources for wireless sensors. This includes the definition of specifications for the interchangeability of various power sources and performance specifications so users can compare different harvesters and choose the optimum power source for each application.

Summary

This case study presents a range of impacts that have occurred as a direct result of Southampton's world leading research in energy harvesting. The exploitation of the technology through Perpetuum has created the market leader in vibration energy harvesting and the applications they have addressed have enabled performance and safety improvements in other business areas. The research team at Southampton have been strong advocates of the technology by contributing to standards and promoting energy harvesting to funding bodies, industry and the general public.

5. Sources to corroborate the impact

[5.1] Contact: President, Perpetuum Ltd - http://www.perpetuum.com/

[5.2] TSB funded project "Energyman", £95,880, start date 1st September 2013

[5.3] Perpetuum press release dated 26/6/13: http://www.perpetuum.com/news.asp

[5.4] Transportation Safety Board of Canada, Railway Investigation Report R01H0005, Derailment: Ottawa Valley Railway, Train 301-043. http://www.bst-tsb.gc.ca/eng/rapports-reports/rail/2001/r01h0005/r01h0005.asp

[5.5] GE Free-standing vibration energy harvester - http://www.ge-mcs.com/download/monitoring/GEA18860-Vibration_Energy_Harvester_FS_r1.pdf

[5.6] GE Customer Success Story - http://www.ge-mcs.com/download/monitoring/GEA17213-CS-Ormen_final%5B1%5D.pdf

[5.7] National Instruments Tutorial: http://zone.ni.com/devzone/cda/tut/p/id/12128

[5.8] http://nickdenbow.wordpress.com/2011/07/08/energy-harvesting-in-use-on-wireless-sensors/

[5.9] EH Network Membership: http://eh-network.org/members.php and resources: http://eh-network.org/resource1.php

[5.10] Competition Brief: Energy harvesting for autonomous sensing, Competition for feasibility and demonstration funding, October 2012. http://www.innovateuk.org/content/competition/energy-harvesting-for-autonomous-sensing.ashx

[5.11] http://www.bbc.co.uk/radio4/science/frontiers_20080512.shtml

[5.12] http://www.bbc.co.uk/programmes/b01mdf08

[5.13] http://www.cheltenhamfestivals.com/science/whats-on/2013/energy-harvesting/

[5.14]http://www.isa.org/InTechTemplate.cfm?template=/ContentManagement/ContentDisplay.cfm&ContentID=87300