Institution: University of Southampton		
Unit of Assessment: 12 Engineering		
Title of case study: 12-01 Vibration energy harvesting – an enabling technology that's driving down costs in the rail industry		
Period when the underpinning research was undertaken: March 1999 – December 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Stephen Beeby	Professor	1992 – present
Neil White	Professor	1988 – present
Nick Harris	Associate Professor	1991 – present
John Tudor	Principal Research Fellow	2001 – present
Bashir Al-Hashimi	Professor	1999 – 2020
Nicola Symonds	Director of nC^2	2011 – present
Geoff Merrett	Professor	2008 – present
Alex Weddell	Lecturer	2009 – present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The University of Southampton's pioneering research into harvesting energy from vibrations led to the spin-out company Perpetuum and together, since August 2013, they have achieved the following impacts:

- Energy harvesting is the key enabling technology behind a self-powered condition monitoring system for rail. The system is now deployed on fleets of trains across 9 countries. Customers include Hitachi Rail, Network Rail, Virgin Trains, Eurostar, and Swedish state-owned train operator SJ.
- The systems are retrofittable and provides maintenance-free condition monitoring of rail components. Perpetuum systems have covered over eleven billion miles and no monitored component has caused a train to fail while in service. [text removed for publication]
- Joint Southampton/Perpetuum Innovate UK projects have improved product performance trebling power output enabling a reduction in harvester size [text removed for publication] and enabling the wireless monitoring of train axles for the first time.
- The data collected can be used to monitor track condition across the network and this is producing a recurring revenue stream [text removed for publication].
- As a result of these activities, Perpetuum turnover has grown [text removed for publication] and the workforce has increased from 10 in 2014 to over 70, the majority being PhD and graduate level engineers.
- Perpetuum were acquired by Hitachi Rail in August 2020.

2. Underpinning research

Energy harvesting from vibrations is the conversion of freely available kinetic energy into electrical power. Vibration energy harvesters (VEH) can be used as a long-term independent power supply for Internet of Things (IoT) devices such as wireless sensors, and therefore avoid the use of batteries, which reduces the maintenance costs incurred in battery replacement. It provides a flexible 'fix and forget' power supply for the IoT improving both practical and economic viability and enabling it to be deployed in inaccessible/hazardous locations since access is not required.

The University of Southampton (UoS) is internationally recognised as a centre of excellence in the development of energy harvesting devices. The underpinning research began in 1999 with a GBP200k *Self-Powered Microsystems* project (EPSRC GR/M35086/01, GBP203,559) led by Professor Neil White, which demonstrated proof of concept of some of the earliest reported

piezoelectric and electromagnetic energy harvesters. The research placed UoS at the forefront of vibration energy harvesting research internationally in both piezoelectric [**3.1**] and electromagnetic [**3.2**] devices.

Professor Steve Beeby and Dr John 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 [**3.3**].

A spinout company, Perpetuum Ltd, was formed in June 2004. The founders – Beeby, Tudor, White and Dr Nick Harris – patented the technology and raised over GBP250k in seed-corn funding. Vital to the company's successful formation was an industrially funded development that the Southampton team carried out in 2003 as a subcontractor for US company RLW Inc. [**3.4**]. This work was funded by the US Office of Naval Research and developed the use of vibration energy harvesting to power the wireless condition monitoring of fire-fighting equipment aboard US naval vessels. These links carried over to Perpetuum, which worked with RLW on its early systems. Perpetuum have since focused on rail applications where the vibration energy harvesting is the key enabling technology behind their wireless condition monitoring systems (see section 4).

Other research projects include the use of vibration energy harvesting for embedded wireless sensors in aircraft (*TRIADE* EU FP 7 Strep project 212859, 1/12/08 – 31/12/12, €5.6M) and the use of energy harvesting techniques in buildings (*TIBUCON* EU FP7 project 260034, 1/9/10 – 31/8/13, €2.4M). Professor B M Al-Hashimi led the *Next-Generation Energy-Harvesting Electronics: Holistic Approach* project (EPSRC EP/G067740/1, 1/10/09 – 31/3/13, GBP722,136), which investigated the energy harvesting system (harvester, electronics and energy storage) as a whole. Key outputs from this project included a modelling tool that combined real world vibration data with different harvester types [**3.5**].

The group has continued to work with Perpetuum though the current REF period and have completed two Innovate UK projects. The first, *Energyman* (1/9/13 – 28/2/15) developed improved power conditioning circuitry and identified more reliable energy storage devices. The second, *WARNSS* (1/5/15 – 31/7/17) developed new smaller harvesters for ancillary train equipment (e.g. gearboxes). Dr Nicola Symonds has also worked with Perpetuum and her work on bearing failure mechanisms has corroborated the Bearing Health Index used by Perpetuum [**3.6**]. Beeby and Symonds worked with Perpetuum and TWI in a third Innovate UK project *MONAXLE* (1/6/18 – 30/5/20) concerned with extending the condition monitoring to include train axles.

The team have published over 100 conference and journal papers (including a benchmark review paper which has been cited over 2830 times [**3.7**]) and edited four books. Beeby and Dr Geoff Merrett established the UK's Energy Harvesting Network, which is now self-sustaining beyond its initial funding period (EPSRC EP/H013458/1, 01/03/10 – 28/02/13, GBP112k), and the team remain at the forefront of energy harvesting research worldwide.

3. References to the research

3.1 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). https://doi.org/10.1049/ip-smt:20010323 *(501 citations)*

3.2 El-Hami, M., Glynne-Jones P.G., James E., Beeby S.P., White N.M., Brown A.D., Hill M. "Design and fabrication of a new vibration-based electromechanical power generator." *Sensors and Actuators A: Physical* 92.1 (2001): 335-342. https://doi.org/10.1016/S0924-4247(01)00569-6 *(505 citations).*

3.3 Beeby S. P., Tudor M.J., Torah R.N., O'Donnell T., Roy S. "A micro electromagnetic generator for vibration energy harvesting." *Journal of Micromechanics and Microengineering* 17.7 (2007): 1257. https://doi.org/10.1088/0960-1317/17/7/007 *(1207 Citations).*

3.4 Prof S P Beeby, **"**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.

3.5 Beeby, S.P., Wang, Leran, Zhu, Dibin, Weddell, Alex S., Merrett, Geoff V., Stark, Bernard, Szarka, Gyorgy and Al-Hashimi, Bashir M. "A comparison of power output from linear and non-linear kinetic energy harvesters using real vibration data." Smart Materials and Structures, 22, (7), 075022, (2013). https://doi.org/10.1088/0964-1726/22/7/075022 *(42 Citations)*

3.6 Corni, I., Symonds, N., Birrell, C., Katsamenis, O. L., Wasenczuk, A., & Vincent, D. "Characterization and mapping of rolling contact fatigue in rail-axle bearings." *Engineering Failure Analysis*, *82,* 617-630, (2017). https://doi.org/10.1016/j.engfailanal.2017.04.012

3.7 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. https://doi.org/10.1088/0957-0233/17/12/R01 *(2830 Citations)*

4. Details of the impact

The research was commercialised in 2004 following the launch of spinout company Perpetuum Ltd [**5.1**] and has since attracted over GBP15m in venture capital. The impacts detailed below include, growth in the business in the impact period, contributions to product innovation, plus reductions in rail maintenance costs for train operators and improved train reliability and safety.

Perpetuum's energy harvesting generators, based on the original Southampton research, has enabled them to develop a self-powered system for real time monitoring of bearings and wheel health on rolling stock that has been widely adopted by the rail industry worldwide. The energy harvesting component supplies sufficient energy to power the sensors, signal processing and wireless communications enabling the system to be a maintenance free, retrofittable solution. This application has been the commercial break though for Perpetuum's vibration energy harvesting technology. The use of batteries or modifying existing wiring looms under trains is not an acceptable approach for the industry, and energy harvesting overcomes these constraints thereby enabling a revolution in condition monitoring on trains. Perpetuum's system is a real example of IoT, where autonomous sensor nodes monitor individual bearings and wheels, and wirelessly transmit the data to a data concentrator located centrally on the train [**5.2**]. The collected data is then transmitted via GSM and stored in the cloud enabling a summary of fleet condition to be available live on the internet with alerts being sent via email or SMS. The wireless nature of the system enables it to be easily retrofitted to existing rolling stock.

The underpinning energy harvesting research is the key enabling technology that makes the Perpetuum system economically and practically viable leading to substantial economic growth in the company. *The* [text removed for publication] *workforce has grown from 10 at the end of the last REF period to over 70 people*, the majority being PhD and graduate level electronic and mechanical engineers, plus further jobs in the supply chain [5.2]. This has enabled Perpetuum to develop a proven system employing a state-of-the-art energy harvester, optimised system electronics and bespoke wireless protocols. Product sales have increased dramatically with the number of deployments increasing from hundreds of trains in 2012 to tens of thousands of wireless sensor nodes across 9 countries (Australia, China, France, Germany, India, Saudi Arabia, Sweden, UK and USA) [**5.2**].

Major example contracts include Sweden's SJ rail who, following the success of the initial 18-month trial deployment on 80 wheels, awarded Perpetuum a contract to monitor its entire fleet of high speed X2000's including a 10-year data service agreement [**5.3**]. Great Northern has fitted sensors to both wheel bearings and gearboxes across its entire fleet of Class 365 trains that run between Cambridge, Peterborough and London King's Cross. Great Northern highlight the improvements to passenger service through reduced breakdowns "This significant investment in state-of-the-art technology will improve the reliability of trains on the route, giving our passengers better journeys. Problems will be highlighted months in advance before these vital components have a chance to break down, avoiding further damage and delays" [**5.4**]. Melbourne Metro has placed a [text removed for publication] order across its Alstom X'Trapolis trainsets following a successful pilot in 2015 [**5.5**]. The partnership with Perpetuum is part of

Metro's rolling stock condition monitoring strategy: "The success of the sensor trials will enable Metro to realise changes in maintenance, which will be driven by quantitative fact. Ultimately, this will lead to significant financial savings in the maintenance of wheel sets and bearing components" [**5.6**].

Further evidence of how Perpetuum's system has revolutionised the maintenance of rail components for rail operators is provided by Southeastern Rail [**5.7** and **5.8**]. Train bearings are designed to last for around 1.4 million miles but in practice early-life failures can begin to occur at around 500,000 miles because of the harsh environment below the train. Southeastern Railway's previous approach to maintenance was to scrap all 64 bearing on each train across its entire 148-train fleet at 480,000 miles. This is because the consequence of failure was so significant as highlighted by Mark Johnson, Engineering Director at Southeastern: "But there may be one bearing that will fail around the 500,000 mile mark. If that bearing fails at the wrong time in the wrong place it has the potential to cause significant disruption or even a possible derailment. Therefore we had to limit our maintenance optimisation due to the potential safety implications" [**5.8**]. Even with this maintenance schedule, every year Southeastern could expect four or five bearings to fail causing trains to be removed from service with passenger journeys interrupted and trains cancelled. There have been no in-service bearing failures since the installation of the Perpetuum system across its fleet. Southeastern are also benefiting from major cost savings, Mark Johnson: "The cost of replacing one bearing against the cost of replacing 64 bearings is significant" [**5.8**]. A similar maintenance schedule was employed by Scotrail who replaced their bearings every 600,000 miles irrespective of condition. The original deployment of Perpetuum's system was expected to deliver a 25% increase in bearing lifespans due to timely fault identification and monitoring [**5.9**] and its success is demonstrated by the announcement in September 2019 of the instrumentation of a third Scotrail fleet [**5.10**]. The impact of the system on reliability is replicated across all deployments: *Perpetuum systems have covered over eleven billion miles and no monitored component has caused a train to fail while in service* [**5.10**]. [text removed for publication]

The research team has continued to work with Perpetuum on Innovate UK projects. The results from these projects have fed directly into the latest product lines offered by the company. In particular, research results from the Energyman project on the efficiency of the power conditioning circuit have trebled the energy captured from the existing harvester. *The WARNSS project investigated the harvester design resulting in a new* [text removed for publication] *smaller harvester*. Together, these improvements have enabled a smaller harvester with sufficient power output to be developed that can be mounted on a wider range of under train equipment. This has enabled the first deployment with a UK freight operator via a Innovate UK funded project which involves the installation of wireless wheelset condition monitoring system on a freight locomotive for the first time [**5.11**]. The smaller harvester is also of benefit when the system is deployed on poor quality rail networks where the high magnitude of impact and shock loads make mounting the original, larger mass harvester, impractical [**5.2**]. The results from the *MONAXLE* project are currently being implemented on a trial deployment in partnership with Hitachi Rail, Eversholt and the First Group as part of a Small Business Research Initiative (SBRI) rail demonstrations: first of a kind 2020 project (TAMON) [**5.12**]. This will expand Perpetuum's monitoring system to include train axles.

A further innovation using advanced data analysis has enabled the self-powered system to also monitor the condition of the track allowing the rail infrastructure operator (e.g. Network Rail) to target their maintenance work more effectively. The vibration data collected contains information regarding the condition of the track and combining this with GPS location provides a real time insight into the condition of the network. The benefits have been recognised by Network rail who have stated "Enabling service trains to report 'live' information back to the maintainer about changes in the [track] condition will provide the necessary time to mitigate delays, limit the dependency on measurement trains and increase the safety for track inspection teams. Real time condition monitoring of the track would also enable a fundamental change in the way the whole system interfaces are managed between operators and infrastructure managers" [**5.8**]. *This, along with the train data itself, has enabled Perpetuum to move towards a Software as a Service (SaaS) business model* [text removed for publication].

The impact from Perpetuum's exploitation of the technology in the rail sector has been recognised by the European Railway Clusters Initiative (ERCI) who represent more than 1000 rail companies from across Europe. The ERCI Innovation awards are judged on criteria including innovation, the economic and social benefits for the railway sector and integration of new digital technologies and Perpetuum was awarded the ERCI Innovation Award 2018 for "Best SME" [**5.13**].

Perpetuum's successful application of Southampton's vibration energy harvesting technology in self powered condition monitoring for the rail industry has culminated the company being acquired by Hitachi Rail in August 2020. This is part of Hitachi's strategy to "advance and digitise its global train maintenance programme" and Perpetuum, including all staff, will "be integrated within Hitachi's railway business of more than 12,000 employees across 38 countries" [**5.14**]

5. Sources to corroborate the impact

5.1 Fifteen year anniversary press release: https://perpetuum.com/2019/09/17/from-start-up-to-making-the-smart-bogie-a-reality-perpetuum-celebrates-15-year-anniversary/

5.2 Corroborating letter from Roy Freeland President, Perpetuum Ltd.

5.3 Impact on product sales, SJ contract: https://perpetuum.com/2017/11/07/perpetuum-wins-long-term-rcm-contract-with-swedish-rail-giants-sj/

5.4 Improved reliability and passenger service: Gerry McFadden, Engineering Director of GTR, https://www.mynewsdesk.com/uk/govia-thameslink-railway/pressreleases/trouble-brewing-great-northern-train-emails-warning-to-engineers-months-before-breakdown-2155005

5.5 https://www.electronicspecifier.com/around-the-industry/perpetuum-win-a-major-contract-with-metro-trains

5.6 Impact on maintenance at Metro Trains Melbourne: Dan Ward, System Engineer, https://www.railwaygazette.com/technology/metro-trains-melbourne-to-test-vibration-harvesters/40592.article

5.7 New Civil Engineer Article "How wireless wheel monitors could identify railway track faults", Ben Cronin, 19th January 2016. https://www.newcivilengineer.com/archive/how-wireless-wheel-monitors-could-identify-railway-track-faults-19-01-2016/

5.8 Case Study: Transforming Southeastern's maintenance schedule: https://perpetuum.com/download/transforming-southeasterns-maintenance-schedule/?wpdmdl=1437&refresh=5d94837cedd7c1570014076

5.9 Scotrail press release: https://www.scotrail.co.uk/about-scotrail/news/trains-running-%E2%80%98perpetually%E2%80%99-perpetuum-software

5.10 Third Scotrail fleet deployment: https://perpetuum.com/2019/09/23/third-scotrail-fleet-to-adopt-perpetuum-onboard-solution/

5.11 Innovate UK project: application in freight: https://perpetuum.com/2019/06/24/1415/

5.12 SBRI FOAK 2020 project: https://perpetuum.com/2020/07/08/perpetuum-awarded-innovate-uk-contract-with-hitachi-gwr-and-eversholt-to-deliver-ground-breaking-train-axle-crack-monitoring-project/

5.13 ERCI Award: https://eurailclusters.com/2018/09/25/congratulations-to-the-erci-innovation-award-winners-2018/

5.14 Hitachi acquisition press release: https://www.mynewsdesk.com/uk/hitachi-rail-global/pressreleases/hitachi-rail-to-acquire-railway-technology-firm-perpetuum-to-accelerate-uk-digitisation-strategy-3025151