Institution: Edinburgh Research Partnership in Engineering

(ERPE: Edinburgh and Heriot-Watt Universities joint submission)

Unit of Assessment: UoA12 Engineering

Title of case study: Embedded intelligent condition monitoring and failure prognosis for critical systems

Period when the underpinning research was undertaken: 2013-2020

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:
Professor David Flynn Dr Valentin Robu Dr Graeme Coapes	Professor of Smart Systems Associate Professor KTP Research Associate	2007 – present 2014 – present 2013 – 2016

Period when the claimed impact occurred: 2016 - 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Researchers in the Edinburgh Research Partnership in Engineering (ERPE), based at Heriot-Watt University, have invented and developed an Environment and Health Monitoring System (EHMS) that can automate and optimise critical asset operations, quantify existing conditions, predict future State of Health (SoH), and detect precursors to asset failure. The impacts of this advanced condition monitoring system are in its adoption and outcomes within the defence, energy and transport sectors. These include:

(A) EHMS was installed, as a world-first, onto critical aircraft handling equipment on HMS Ocean, the UK's helicopter carrier and Fleet Flagship of the Royal Navy;

(B) EHMS architecture was chosen by Siemens Energy to be a fundamental sub-system in the development of their new '*Assetguard*', an on-line condition monitoring platform. EHMS reduced *Assetguard* development costs by 40% and resulted in enhanced monitoring capabilities;

(C) As a consequence, Siemens invested GBP 1 Million in the UK to support future research and development;

(D) EHMS was incorporated by Denchi Group Ltd into their SLICEMARINE lithium-ion battery technology (for marine propulsion applications) and was applied to a marine passenger transport system, winning the British Renewable Energy Prize 2018 for Decarbonisation of Transport.

2. Underpinning research

In recent years and across a myriad of industries, there has been a realisation that in order to optimise the Remaining Useful Life (RUL) of assets and to maintain optimal system level performance, a transition to predictive maintenance from reactive and traditional condition-based monitoring and maintenance is required. ERPE researchers have been leading research in the development of Environment and Health Monitoring Systems (EHMS). The drivers for EHMS are the need to automate and optimise critical asset operation, quantify existing conditions, predict future State of Health (SoH) and detect precursors to asset failure.

A key challenge for power distribution and transmission system operators is to relate the retrofitting of monitoring systems to support asset management, aligned with the continuity of service within the electricity supply network. [3.1] demonstrated how a Smart System Integration approach, utilising a wireless sensor network (WSN), can provide a low cost and scalable sensor platform for in-situ sensing of assets within substations. The findings of this research

demonstrated the advantageous features of WSNs, namely low cost, rapid deployment, reliable and secure data transfer, adaptive and scalable sensor platform.

The energy sector is driven by, and regulated to ensure, security of supply to end-demand customers, as well as to deliver return on their shareholders' investments. This predicates a need to invest wisely to maximise the RUL of the existing, ageing asset base in the electricity supply networks. In the UK, depending on location, an unscheduled substation outage can cost the system operator of the order of GBP 1 Million per day and the annual costs of maintaining transmission and distribution network assets in the UK is over GBP 5 Billion.

ERPE staff developed a novel approach [3.2] to hierarchical predictive maintenance of assets through a distributed architecture, represented as domain knowledge-based systems that could provide a transportable, adaptive platform that could be deployed in other systems containing similar multiple assets.

The research detailed in [3.3] combined the synergies of data, modelling and fusion-based prognostic methods to underpin and develop functionalities with embedded intelligence for use in asset management platforms across other readiness-critical areas. In these applications, critical assets require to be maintained in operational readiness for decades, whilst deployed in dynamic operating regimes and in arduous environments. For example, [3.3] demonstrated detailed Failure Mode Effect Analysis (FMEA) of a power relay and this illustrated how intelligent asset management can be enabled to predict the RUL of ship and submarine sub-systems, and to inform product development.

The continuing functionality, reliability and efficiency of critical assets from component to system level depends on being able to monitor status, condition, operating ambient environment and loadings in real time. Following data acquisition, transmission, processing and analysis it is then essential to be able to understand their current SoH and reliably predict their future SoH and RUL, either to schedule maintenance interventions or to ensure timely replacement before failure. Incorporation of sensors and data delivery technology during build can provide significant volumes of data. Intelligent analysis of these data can be fast and relatively cheap, but can also lead to protecting readiness-critical, capital-intense assets and to preserving human safety. Upgrading or modernisation of these system assets can be prohibitively expensive so early identification can reduce such costs through an EHMS approach.

The ERPE EMHS methodology for forecasting asset health and optimising operations is based on Prognostics and Health Management (PHM) methods that permit the assessment of the reliability of the asset in application conditions. EHMS combined (1) sensing, (2) monitoring, (3) interpretation of environmental, operational, and performance-related parameters to indicate an asset's SoH [3.4]. The ERPE research involved in each step included.

1. A detailed study into the operational decision support requirements of the asset management system. This included the identification of potential Failure Modes, which could lead to a failure event of a critical component or sub-system within the asset. Sensing technologies were then designed and integrated to detect precursors and early onset failures modes. These early indicators would support more accurate forecasting of the assets SoH.

2. Timely acquisition and rapid Big Data Analysis within operational systems. Data analysis to support effective monitoring needs to be able to detect, locate, classify and diagnose events within the data that are indicative of precursors to failure. The ERPE models involved the integration of statistical and machine learning based algorithms.

3. Integrated real time environmental, operational, and performance-related descriptions were created within a reliability ontology of the asset. This reliability model maps the interdependencies, relationships, of components and sub-systems throughout the asset. Data from sensed and non-sensed components are integrated in near-to-real time to provide a holistic and whole system analysis.

Implementation of the above three factors provided a combined structure for the EHMS with the ability to sense and interpret the parameters indicative of (a) Performance degradation, (b)

Physical or electrical degradation (c) Changes in a life-cycle profile, such as usage duration and frequency, humidity and vibration. This allowed the EHMS to optimise the performance of the asset by providing intelligent adaptive planning or control feedback into the operation of the asset and to optimise its operational life by reducing the probability of a failure [3.5]. The application of EHMS to electrical systems in marine passenger vessels was also undertaken via [3.6].

3. References to the research

[3.1] **Conference:** Huynh, N., Robu, V., Flynn, D., Rowland, S., & Coapes, G. (2017) Design and demonstration of a wireless sensor network platform for substation asset management. Paper presented at CIRED 2017, Glasgow, United Kingdom. https://pure.hw.ac.uk/ws/portalfiles/portal/16131210/oap_cired.2017.pdf

[3.2] **Conference:** Miguelantildeez-Martin, E., and Flynn, D. Embedded intelligence supporting predictive asset management in the energy sector. In Proceedings of the Asset Management Conference 2015 (pp. 7-14) https://doi.org/10.1049/cp.2015.1752

[3.3] **Conference:** Flynn, D., Herd, D. S., Lofting, D., Record, P. M., and Skinner, N. (2014). Health and usage monitoring systems: enabling the future prediction of remaining useful life of submarines. Paper presented at International Naval and Engineering Conference, Amsterdam, Netherlands. https://researchportal.hw.ac.uk/en/publications/health-and-usage-monitoring-systems-enabling-the-future-predictio

Note: All conference papers were peer reviewed.

[3.4] **Journal:** Huynh, N., Robu, V., Flynn, D., Rowland, S., & Coapes, G. Design and demonstration of a wireless sensor network platform for substation asset management. CIRED - Open Access Proceedings Journal, 2017(1), 105-108. https://doi.org/10.1049/oap-cired.2017.0273

[3.5] **Patent**: EP3621096A1 - Gas monitoring system for gas-insulated switchgears https://patents.google.com/patent/EP3621096A1/en

[3.6] **Journal.** Tang, W., Roman, D., Dickie, R., Robu, V., & Flynn, D. (2020). Prognostics and Health Management for the Optimization of Marine Hybrid Energy Systems. Energies, 13(18), [4676]. https://doi.org/10.3390/en13184676

4. Details of the impact

The underpinning ERPE research [3.1-3.4] led the key stages of the development and trials of the Environment and Health Monitoring System (EHMS) for advanced condition monitoring of critical assets [3.6]. This has resulted in multiple impacts across a range of sectors, including defence, marine, energy and transport. The resulting key impacts of the award-winning collaborations with industry are outlined as follows:

(A) Environment and Health Monitoring System (EHMS)

ERPE researchers have enjoyed a strategic collaborative research partnership with MacTaggart Scott Ltd since 2011. The industry-academic partnership received the 2017 Interface Award for Sustainable Partnership [5.1] and drove planning and support for additional research. This partnership led the development of EHMS.

MacTaggart Scott benefited from the research by having a world-first installation of EHMS on critical aircraft handling equipment on HMS Ocean, the UK's helicopter carrier and Fleet Flagship of the Royal Navy. This gave the Royal Navy, for the first time, insight into how equipment such as aircraft handling systems are utilised in the field (at sea), while also providing access to previously inaccessible data on critical systems [5.2].

EHMS also provided new insight into the specific loading/duty cycles of the aircraft handling equipment for McTaggart Scott. This informed future bill-of-material (BOM) and factor-of-system

(FoS) estimates in the design for reliability (DFR) process. EHMS also provided failure precursor analysis and optimised control of hydraulic systems in the aircraft handling system.[5.2]

In 2015 MacTaggart Scott were invited to present to the Australian Submarine Institute on the applications of the EHMS, and they stated in their summary "*Condition monitoring for outside pressure hull submarine equipment has historically been unachievable due to the need for environmentally capable, power efficient sensing technology with the capability to operate with little or no interaction with the internal submarine environment. Development of the EHMS system enables meaningful data on system performance and operating environment to be gathered throughout a vessel deployment, in a package that requires no pressure hull penetrations*", demonstrating the versatility and unique insights that EHMS can provide [5.3].

MacTaggart Scott described the prognostics research as "*ground breaking*" [5.3] and confirmed that the development of the EHMS approach has led to international market growth for the company in Australia and North America [5.2].

(B) Siemens *Assetguard*

Siemens Energy needed to replace their legacy Integrated Substation Condition Monitoring (ISCM) platform to take advantage of the advances in data acquisition, processing and advisory communications that new sensors, signal processing and data handling enabled. A Knowledge Transfer Partnership (KTP) from 2013-2016 led to the design and development of *Assetguard,* a novel sensor technology and fusion based prognostics for the next generation of condition monitoring systems for assets on the grid.

In April 2015, during the early project trials of the EHMS and guided by Siemens collaborators, ERPE staff and doctoral trainees in the EPSRC CDT in Embedded Intelligence researched, designed, built and tested a sensor which could detect partial discharge or localised breakdown within voids in the insulation of high voltage electrical systems. These voids are often the first sign of a potential insulation failure and asset outage. *'The system would allow operators to pinpoint and deal with the problem before it would have a chance to compromise power supply'* [5.4]. R&D Product Lifecycle Manager at Siemens, Scott Rowland, said, "*The motivation and ingenuity shown by these (EPSRC Doctoral) students was outstanding. The project highlighted the great rewards that can be provided by close collaboration between industry and local universities*" [5.4].

The resultant development and outcomes stemming from the KTP resulted in Siemens achieving a 40% saving in total project development cost compared to that of its predecessor [5.5]. The modular design of the *Assetguard* platform also made it more amenable to customisation enabling improved access to international markets [5.5]. EHMS is now to be found [5.5] in *Assetguard* across several application domains denoted: *Assetguard* PDM (Partial Discharge Monitoring); *Assetguard* CBM (Circuit Breaker Monitoring); *Assetguard* GDM (SF_6 Gas Density Monitoring) and *Assetguard* MVC (Medium Voltage Circuit Breakers).

(C) Siemens UK investment, patents and partnership

The technical and commercial success of the *Assetguard* platform development led to Siemens investing an additional GBP1,000,000 into the UK [5.6] to support future research and development, jobs and innovation.

A patent (EP3621096A1) [3.5] also resulted from this research collaboration.

"*The knowledge transfer partnership between Siemens and Heriot-Watt University has demonstrated how academia and industry can work together to successfully deliver a paradigm shift in technical capability and resultantly an enhanced service to the clients we serve. With this new technology platform we will continue to grow as a business, as we strive to not only meet but exceed our clients' expectations*." – R&D Team Leader, Siemens [5.6]

(D) SLICE Marine

ERPE researchers collaborated with Denchi Power (UK company, part of the Denchi Group) in the academic and industrial HyFES consortium, which was supported by Innovate UK. EHMS

was incorporated by Denchipower into their SLICEMARINE lithium-ion battery technology for marine propulsion and other applications.

The rapid commercialisation of SLICE arose from the results of in-field research and trials of EHMS. Sponsored by Innovate UK and EPSRC, the project measured three key performance indicators namely; energy performance, environmental metrics and asset health. It was installed on the MBNA Thames Clipper catamaran passenger vessel in London, resulting in a 75-80% reduction in fuel costs over their diesel engine propulsion system [5.7].

The asset management system also reduced operation and maintenance costs of the vessel by providing an advancement from time-based maintenance to predictive maintenance. MBNA vessel engineers and Denchi staff were also able to use the EHMS in SLICE to support autonomous propulsion that reduced noise and pollutant emissions in built-up residential areas adjacent to the Thames operations. The Chairman and Managing Director of Denchi Group Ltd stated, "*The Heriot-Watt team was instrumental to the success of the* Hybrid Fusion Energy System (HyFES), demonstrating *the power that a data driven approach has on determining the prognostics and asset integrity of any platfor*m" [5.7]. This research and resultant impacts of the Thames Clipper vessel was awarded the British Renewable Energy Prize 2018 for Decarbonisation of Transport [5.8]

5. Sources to corroborate the impact

[5.1] Scottish industry-academia Knowledge Exchange Awards 2017 for MacTaggart Scott and ERPE Heriot-Watt University for sustained partnership supporting innovation, enterprise and growth.https://interface-online.org.uk/news/winners-scottish-knowledge-exchange-awards-announced-0
[5.2] Development Manager of R&D, MacTaggart Scott Ltd
(can be contacted to confirm confirming implementation of EHMS and utilisation on HMS Ocean)
[5.3] Mactaggart Scott paper "Health Monitoring of Marine Equipment" presented to the Australian Submarine Institute on the capabilities of the EHMS, described research as ground breaking and cited advantages as no pressure hull penetrations and new insights from EHMS.
https://www.mactag.com/uploads/tinymce/Health%20Monitoring%20of%20Marine%20Equipment.pdf
[5.4] News article on Siemens early partnership in the use of EHMS, linkages to KTP project and role of the ERPE EPSRC Doctoral Training Centre based at the Heriot-Watt Campus
[5.4A] The Next Generation of Power Network Condition Monitoring
https://www.hw.ac.uk/uk/schools/engineering-physical-sciences/institutes/sensors-signals-systems/news.htm
[5.4B] Bright sparks help to keep the lights on.
https://www.hw.ac.uk/news/articles/2015/bright-sparks-helping-to-keep-the-lights-on.htm
[5.5] Evidence of the development of the Siemens *Assetguard* System and incorporation of EHMS. R & D Team Leader, Siemens Ltd Hebburn, UK
(can be contacted to confirm creation and application of the Siemens *Assetguard* System)
[5.6] R&D Product Lifecycle Manager, Siemens Ltd, USA,
(can be contacted to confirm inward investment from Siemens and establishment of Global Centre of Competence in High Voltage Monitoring and Diagnostics)
[5.7] Executive Chairman / Managing Director, Denchi Group
(can contacted to confirm new product development and implementation)
[5.8] British Renewable Energy Awards 2018 – awarded for Low Carbon Transport - MBNA Thames Clipper project. https://www.r-e-a.net/renewable-energy-industry-celebrates-record-breaking-year-at-prestigious-awards-ceremony/