Institution:	**Lancaster University**
Unit of Assessment:	**UoA15 (General Engineering, Main Panel B, Sub-Panel 15)**
Title of case study:	**Uptake of Intelligent Microsystems by Multinational Companies through Assistance in On-Line Test and Reliability Modelling Technology Developed at Lancaster**

1. Summary of the impact

The key impact is to have improved the economic performance of both multinational companies and SMEs through the introduction and performance enhancement of new electronic products.

Lancaster's research on reliability modelling technologies for use in the characterisation and optimisation of the reliability of MEMS (Micro-Electro-Mechanical Systems) products such as accelerometers and gyroscopes has been used by ST Microelectronics to achieve mass market penetration of its MEMS. Specifically, the market share of ST (a French-Italian multinational electronics and semiconductor manufacturer) has doubled to $900M since 2008, with its MEMS accelerometers and gyroscopes now being found in, inter alia, Apple's iPhone, iPad and iPod.

Lancaster's test engineering research has also delivered a novel self-test technology that can be activated during normal operation of a MEMS based system. This capability has been integrated into an inertial device commercialised by QinetiQ for classified applications. Additionally, through assisting BCF-Designs (a UK SME specialising in electronic test systems for the military and civil aerospace sectors) in the development of its R&D portfolio and associated intellectual property in the area of on-line (in situ) testing, research conducted at Lancaster directly supported the tripling of BCF's turnover to £9M and more than doubling of its sale value to £12.5M (to ULTRA Electronics, 2008).

2. Underpinning research

MEMS (Micro Electro Mechanical Systems) are miniaturised components with moving structures having dimensions that are typically between 100 nanometers and 100 microns. These components are manufactured from a substrate material using etching and material deposition processes rather than mechanical assembly and can be manufactured in large quantities at low cost. The technology is well suited to sensing and actuation, offering more compact solutions than conventional technologies. Applications do however typically require high quality at low cost for consumer markets and fault tolerance in aerospace, defence, medical and transport applications. On-line test and efficient reliability modelling are hence crucial technologies for these products

Led by Professor Andrew Richardson, underpinning research at Lancaster has focused on the reliability modelling, characterisation and optimisation technology needed to demonstrate that the active structures in MEMS devices can withstand the mechanical and thermal stress typical in consumer market applications. It has also demonstrated that the reliability required by potential customers, together with the test features needed for low cost manufacture and in-field self-test, is achievable.

Early research by Richardson's team at Lancaster under the EU FP4 "ASTERIS" Project 26354 (1998-2001, 1.65 million euro) explored the potential for utilising behavioural methods for modelling defects and degradation across the electronics to micromechanical interface within accelerometers, magnetometers and pressure sensors. This built on new inventions at Lancaster **[Reference 1]** involving threshold comparator based level checking for validating the integrity of microsensors through electrical-only design for test concepts **[Reference 1]**.

Further research conducted by the Richardson Team at Lancaster delivered the first validated and practical solutions for component level fault modelling in microstructures. These findings were initially peer reviewed and published at the SPIE Design, Test and Packaging Conference in 2003 (doi: 10.1109/DTIP.2003.1287023) and extended through invited publication in *Analog Integrated Circuits and Signal Processing* in 2004 **[Reference 2]**. This research was carried out in collaboration with ST Microelectronics (a world leading French-Italian multinational electronics and semiconductor manufacturer with 50,000 employees worldwide and annual revenue of $9.7 billion) under the EU FP5 project "MACROS" IST-2001-34714 (2002-2005, 1.6 million euro) that produced new behavioural modelling techniques based around applications of Cosserat theory developed

since 2002 by Professor Robin Tucker, Head of Lancaster's Industrial Mathematics Group and a member of UoA15.

This insight opened the possibility of building component models of MEMS structures under different stress conditions that would be difficult if not impossible to construct using conventional analytical techniques. The methodology also supported the modelling of package-induced and residual stress on the operation of the component. All of this research was conducted by Richardson's Team at Lancaster and used to validate novel capacitance and optical methods for the exploration of mechanical fatigue in the structural material used in ST Microelectronics MEMS products. The work also covered reliability hazards such as residual and package stress induced in a commercial test structure **[Reference 3]**. Within this research the Lancaster team invented both the modelling methodology and created the specific reliability models for the test structure studied. This research was published in *Microsystem Technologies* **[Reference 3]** and also selected through peer review for publication in the *ST Journal of Research* (Volume 3 - Number 1 – MEMS, 2005 ISSN:1828-2105).

The extension of this research through the European Network of Excellence in Design for Micro & Nano Manufacture (PATENT-DfMM, FP6-507255 6.2M€, 2004-2009) involved the application of the behavioural modelling strategy deployed on the test structures of **Reference 3** to a silicon gyroscope test structure supplied by ST Microlectronics **[Reference 4]**. This research was carried out in collaboration with ST and informed the evolution of their gyroscope MEMS technology and its subsequent uptake by companies including Apple. The methods used involved the novel application of component level fault models based on Cosserat theory that were realised by the Richardson Team and Till Wiegand, a student seconded to Lancaster from the University of Bremen.

This collaborative work with ST Microelectronics stimulated further research by Richardson's Team into methods of monitoring integrated MEMS technology using test methods that can be activated whilst the device is in normal use in the field. Initial research at Lancaster involved the invention of the "Bias Superposition" method that stimulated interest from QinetiQ, the French National Centre for Scientific Research (CNRS), the University of Paris and Oxley Developments. This work resulted in a major paper in *Sensors and Actuators A*, written in collaboration with CNRS, QinetiQ and the University of Paris **[Reference 5]**. The core technique associated with the reported "Bias Superposition" method, involving the injection of test stimuli into the bias chain, was invented at Lancaster. Applications research with QinetiQ was also delivered by Lancaster University; subsequent application of the Lancaster method to a ST Microelectronics Magnetometer was carried out by CNRS and the University of Paris**. Reference 5** also documented the invention and application of a test strategy based around bias superposition involving the measurement of a time constant from a low frequency superimposed test signal for an electrochemical sensor from Oxley Developments. This research was again carried out by the Richardson Team at Lancaster.

Further enhancements to the bias superposition method through the use of a signal encoding and a covariance algorithm were also invented by the Richardson Team. The outputs of this research were initially peer reviewed through a contribution to the IEEE European Test Symposium 2007 and extended through an invited submission to the *Journal of Electronic Testing* in 2008 **[Reference 6]**.

3. References to the research

International academic and industrial co-authors are in italics. **Lancaster authors are in bold**. 100% of research outputs submitted by Lancaster to RAE2008 under UoA25 were judged to be 2* or better. **References 3, 4 and 5** were included in that submission and best represent the quality of the work undertaken.

1. *Olbrich, T (Austria Mikro Systeme Int.),* **Richardson, A.M***., Vermeiren, W. (Fraunhofer – Dresdon) and Straube, B. (Fraunhofer – Dresdon)* "Integrating Testability into Microsystems" Journal of Microsystem Technologies vol. 3, no. 2, 1997, pp 72-80.

2. **Wang, C.; Liu, D.; Rosing, R**.; *De Masi, B (ST Microelectronics)*.; **Richardson, A**., "Construction of nonlinear dynamic MEMS component models using Cosserat theory," Analog Integrated Circuits and Signal Processing, Volume 40 Issue 2, August 2004, Pages 117 – 130, doi: 10.1023/B:ALOG.0000032593.34671.fa

3. *Eleonora Ferraris , Irene Fassi (IITA), Biagio De Masi (ST Microelectronics)*, **R. Rosing, A. Richardson** "A Capacitance and Optical Method for the Static and Dynamic Characterisation of MEMS Devices", Springer Journal of Microsystems Technologies, Volume 12, Numbers 10-11, pp 1053-1061, September, 2006, doi : 10.1007/s00542-006-0163-6.

4. *T. Wiegand, D. Peters, R. Laur (Uni Bremen)* **A. Richardson, R. Rosing**, *M. Del Sarto, L. Baldo (ST Microelectronics)* "Model based design optimization of micro mechanical systems, based on the Cosserat theory" Proceedings of Optimization of Electrical and Electronic Equipment OPTIM'08, pp33-38, 22nd-24th May 2008, doi: 10.1109/OPTIM.2008.4602340;

5. **C. Jeffrey, Z Xu, A Richardson**, *F. Mailly, P. Nouet, F Azais (LIRMM), R.J.T. Bunyan, D.O. King (QinetiQ), H. Mathias , J.P.Gilles (IEF, Paris)* "Sensor testing through bias superposition" Sensors and Actuators, A: Physical May 1, 2007 136 1 441-455, doi 10.1016/j.sna.2006.11.030.

6. **N. Dumas**, **Z. Xu, K. Georgopoulos**, *R. J. T. Bunyan (QinetiQ)* , **A. Richardson** "Online Testing of MEMS based on Encoded Stimulus Superposition" Springer Journal of Electronic Testing, Volume 24, Number 6, December, 2008, pp555-566, DOI 10.1007/s10836-008-5090-2

4. Details of the impact

The research described in §2 has given rise to economic impacts on and for multinational companies and SMEs through:

- the transfer of reliability modelling and evaluation methods into the design and manufacturing flows of ST Microelectronics, assisting them to achieve mass market penetration of their inertial devices in several commercial sectors including the gaming and the cell phone markets;
- the transfer of the Design for Test solutions arising from this research into the UK SME BCF-Designs Ltd. This has resulted in a new Research & Development program funded by both private and public sector sources resulting in new contracts for BCF-Designs and an increase in the company's value. The transfer has also assisted with the dissemination of enabling test technology into the structural health monitoring sector;

Specific details are as follows:

The application of the research described in **References 2 and 3** and later in **Reference 4** has supported ST Microelectronics **in commercialising new products & processes**. The research reported in **References 2 and 3** was used to provide reliability data associated with the materials, fabrication process and moving structures within MEMS test devices that was essential to the uptake of ST Microelectronics MEMS 3D accelerometers in the Wii gaming console by Nintendo in September 2006 that remain in use today **[Vigna_2006]**.

The characterisation technology developed through this research, together with further work with ST Microelectronics on a MEMS gyroscope **[Reference 4]** in 2008 that also delivered an optimised design, has provided ST Microelectronics with the enabling reliability analysis tools **[V_2012]** that have supported the evolution of ST Microelectronics MEMS products from a $30M dollar market in 2006 to $450M in 2008 and $900M in 2012 **[Yole 2102]**. This growth has been primarily due to the uptake of ST Microelectronics inertial devices, and in particular the gyroscope technology, by several leading cell phone manufacturers, including Apple, over the REF period. In 2011 the exclusive use of ST Microelectronics accelerometers and gyroscopes in Apple iPhones, iPads and iPods accounted for over half of ST microelectronics MEMS revenue **[isupply 2012]**. The enabling research in **References 2, 3 and 4** has provided ST Microelectronics with a means to validate, through simulation, the effectiveness of several reliability characterisation methods in revealing potential reliability hazards within manufactured structures. It also supported research that validated the shock resistance of the original 3D accelerometers and gyroscope sensor to 10,000g, essential for robustness requirements in consumer applications.

Between 2006 and 2009 ST Microlectronics, through Beneddetto Vigna (now Executive Vice President and General Manager of ST's Analogue, MEMS & Sensors Group), chaired the Industrial Advisory Board for the Lancaster-led Network of Excellence in Design for Micro manufacture (PATENT-DfMM, FP6-507255) that supported further research on design for test strategies. This research delivered solutions to further improve the outgoing quality of MEMS based products by

providing low cost, high fault coverage embedded test solutions that utilised electrical only test techniques. This led to the research published in **Reference 5** that included work on an ST Microelectronics magnetometer together with a further two demonstrators from Oxley Developments (an electrochemical sensor) and QinetiQ (a MEMS accelerometer). The bias superposition research with QinetiQ on the accelerometer was extended **[Reference 6]** and transferred into QinetiQ during 2008. Although the use of this knowledge is classified, QinetiQ are willing to testify that its impact on their MEMS development programme has been significant **[P_2012]**.

A feasibility study into the use of the inventions in **Reference 5** for in-situ testing of aircraft wiring using intelligent connectors and embedded instruments was carried out by Lancaster and Heriot Watt Universities in 2006 under the PATENT-DfMM Network of Excellence. This research project was approved by the Industrial Advisory Board of the Network under the chairmanship of Beneddetto Vigna (ST Microelectronics, see above). The results from this study underpinned a grant award to Lancaster University of £380K (2007-2010) from the company BCF-Designs to address on-line (in-situ) testing of aerospace wiring systems. The research led to both public grants from the Department of Trade and Industry and a US Navy contract into BCF-Designs with the associated impact of the research on the company's products and services **improving the performance of BCF-Designs** from a turnover of £2.5M in 2007 to £9M in 2008. The value of the company consequently increased from an unsolicited offer of £5-6M prior to the launch of this research to their sale value of £12.5M to ULTRA Electronics in 2008 **[S_2008]**. This increase in turnover and value was primarily enabled through the Research and Development portfolio and associated intellectual property developed through the research including in-situ test signal injection, nodal monitoring and superposition of acoustic test stimuli with Lancaster University.

Further impact on the **performance of existing businesses by consultancy and services** was achieved through the launch of several workshops and co-authoring of an associated expert report by Lancaster University that focused on the application of embedded test technology within the structural health monitoring sector **[Nexus_2008]**. This work has had positive impacts on the business development of several companies – including Centrica, who commissioned Lancaster to conduct a study into the use of miniaturised health and usage monitoring technologies for instrumenting off-shore gas drilling installations.

5. Sources to corroborate the impact

[Vigna_2006]: Flavio Lorenzelli, Benedetto Vigna, "MEMS: The secret revolution" ST Journal of Research (Volume 3 - Number 1 – MEMS, 2005 ISSN:1828-2105).

[V_2012]: Corroboration, by contacting Executive Vice President STMicroelectronics, of the role that Lancaster's research played in their being able to demonstrate the reliability of their MEMS products, leading to MEMS product uptake by several consumer electronics manufacturers with a consequent increase in company value to in excess of $900M.

[Yole_2012]: Global position of ST Microelectronics: http://www.i-micronews.com/upload/figures/Illustration_Top_30_MEMS_Company_ranking_March_2012.pdf).

[iSupply 2012]: Jérémie Bouchaud "Press Release: STMicroelectronics Leverages Apple Design Wins to Increase Consumer and Mobile MEMS Leadership" 5th April 2012

[P_2012]: Factual statement from ex-Research Funding Manager, QinetiQ, confirming that the transfer of on-line test strategies and results to QinetiQ had significant impact on the QinetiQ MEMS programme.

[S_2008]: Factual statement from ex-Technical Director of BCF Designs corroborating the impact that Lancaster's miniaturised health and usage monitoring and embedded test engineering research had on increasing the sale value of BCF-Designs.

[Nexus_2008]: Microsystems for structural health monitoring" Richardson, Andrew ; Van Heeren, Henne ; Neylon, Sean. European Commission, 2008. http://www.research.lancs.ac.uk/portal/en/publications/microsystems-for-structural-health-monitoring%28d6c8880d-09ea-409e-b465-c4f4284a989a%29.html