Institution: Lancaster University

Unit of Assessment: 12, Engineering

Title of case study: Use of Lancaster's research in reliability modelling and characterisation technology within ST Microelectronics inertial MEMS products leads to economic impact through sales and diversification of markets.

Period when the underpinning research was undertaken: 2002-2010

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:
Andrew Richardson	Professor	01/08/1995 – present

Period when the claimed impact occurred: 2014-2020

Is this case study continued from a case study submitted in 2014? Y

1. Summary of the impact

Lancaster's research on reliability modelling technologies has been used by ST Microelectronics (STM) to achieve mass market penetration of its inertial MEMS (Micro-Electro-Mechanical Systems) products. Since 2014, these inertial devices that include accelerometers and gyroscopes have contributed USD3.5 billion in sales revenue for ST Microelectronics. Markets over this period include the iPhone 4 and 4S (included in 15 million units sold between January and September 2014), the iPhone 5C (included in 22 million units sold between 2014 and 2015), the Nintendo Wii and Wii U (included in 11.9 million units sold between 2014 and 2017) and the Nintendo Switch (70 million unit sold between 2017 and 2020). Penetration into the automotive market has also been achieved that has built upon both reliability and test methodology research delivered to ST Microelectronics by the Lancaster team.

2. Underpinning research

MEMS (Micro Electro Mechanical Systems) are miniaturised components with moving structures having dimensions that are typically between 100 nanometres 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 University 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, EUR1.65 million) had 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 involving threshold comparator-based level checking for validating the integrity of microsensors through electrical-only design for test concepts.

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 (and extended through invited publication in Analog Integrated Circuits and Signal Processing in 2004 [3.1]. This research was carried out in collaboration with ST Microelectronics (a world leading French-Italian multinational electronics and semiconductor manufacturer with 46,000 employees worldwide and annual revenue of USD9.7 billion) under the EU FP5 project "MACROS" IST-2001-34714 (2002-2005, EUR1.6 million) 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. 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 behaviour of the MEMS inertial devices. 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 [3.2]. 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 [3.2] 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 EUR6.2 million, 2004-2009) involved the application of the behavioural modelling strategy deployed on the test structures of [3.2] to a silicon gyroscope test structure supplied by ST Microelectronics [3.3]. 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 [3.4]. ST Microelectronics, although not included in the author list chaired the industrial advisory board reviewing, advising and guiding this work. 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 [3.5] was also delivered by Lancaster; subsequent application of the Lancaster method to a ST Microelectronics Magnetometer was carried out by CNRS and the University of Paris.

3. References to the research

International academic and industrial collaborators are indicated as such in parentheses following the co-author name. Lancaster authors are in bold.

[3.1]. **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, pp.117 – 130

[3.2]. 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.

[3.3]. 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, pp.33-38, 22nd-24th May 2008.

[3.4]. **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 1st May 2007, 136, 1, pp.441-455.
[3.5]. **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, pp.555-566.

Quality Indicators:

100% of research outputs submitted by Lancaster to RAE2008 under UoA25 were judged to be 2* or better. References [3.2] and [3.4] were included in that submission and best represent the quality of the work undertaken.

EU FP5 project "MACROS" IST-2001-34714 (2002-2005, EUR1.6 million)
European Network of Excellence in Design for Micro & Nano Manufacture (PATENT-DfMM, FP6-507255, EUR6.2 million, 2004-2009)

4. Details of the impact

The author's REF2014 case study detailed the economic impact, of the research described in Section 2, on the ability of ST Microelectronics to secure contracts for their inertial devices from multinational companies including Nintendo (Wii). This continuing case study details the ongoing economic impact on ST Microelectronics, specifically through sales revenue associated with inertial MEMS products that totals USD3.5 billion since 2014. These devices have had a specific impact on a number of industry sectors including consumer and automotive electronics. Significant contributors to this overall impact [5.4] include the LIS331DLH accelerometer and the L3G4200D gyroscope in the iPhone 4 and 4S (included in 15 million units sold between January and September 2014) [5.2], the gyroscope in the iPhone 5C (totalling 22 million units sold in 2014 and 2015) [5.2], the Nintendo Wii and Wii U (included in 11.9 million units sold between 2014 and 2017) [5.7] and the 6-axis inertial sensors in the Nintendo Switch (totalling 70 million sales between 2017-2020) [5.1]. In the automotive market, the release of products including the AIS328DQ 3 axis accelerometer, the A3G4250D 3 axis gyroscope and the ASM330LHH inertial measurement unit has built on the ability of ST Microelectronics to deploy design for reliability and reliability evaluation methodologies to deliver very low field failure rates at low cost. Here, the work described in section 2 has assisted ST Microelectronics to establish a solid platform for success in the airbag market with growing applications in roll detection and advanced driver assistance systems [5.3].

The application of the research described in [3.1], [3.2] and later in [3.3] supported ST Microelectronics in commercialising new products and processes. The research reported in [3.1] and [3.2] was used to provide reliability data associated with materials, the fabrication process and moving structures within MEMS test devices that was essential to the uptake of ST Microelectronics MEMS accelerometers and gyroscopes. The characterisation technology developed through this research, together with further work with ST Microelectronics on the gyroscope [3.3] also delivered an optimised design and provided ST Microelectronics with enabling reliability analysis tools. The enabling research [3.1-3.3] also 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. The penetration of ST Microelectronics inertial sensors into the automotive market has been supported by all the work described above with collaborative research associated with embedded test [for example 3.5 where ST Microelectronics where advisers] providing an important contribution to the methodology associated with "Aerospace Quality at Automotive Prices".

Benedetto Vigna, President of the Analog, MEMS and Sensor Group and member of the executive group for ST Microelectronics confirmed that the *"research collaboration started in 2002 through the MACROS EU project (IST-2001-34714) and extended into the PATENT DfMM Network of Excellence (507255) [outputs include 3.2- 3.5] and beyond during which time your team carried out the modelling and characterisation work associated with the reliability evaluation of our MEMS inertial sensing technology. This work had a significant contribution to*

ST Microelectronics in both our ability to prove the reliability of this technology and hence achieve market penetration that included the Nintendo Wii and subsequently the Apple iPhone. The modelling and reliability evaluation methodologies that are used today still find their roots in the work that you and your extended team led within these two European projects carried out in collaboration with the MEMS team in ST Microelectronics." [5.4]

Of significance in the context of market retention is the ease in which reliability evaluation methodologies can be ported between product generations. The 45% footprint reduction achieved within the gyroscope in the iPhone 5 [5.5] relative to the iPhone 4 required both a reduction in the critical dimensions in the MEMS structure and advances in the packing process whilst maintaining competitive levels of reliability. As [5.4] and the extract above from ST Microelectronics indicate, the methodologies delivered have also contributed to this capability and supported the evolution of existing markets with Nintendo [5.6].

In conclusion, the impact of the research detailed in sections 2 and 3 on the ability of ST Microelectronics to penetrate key consumer markets, including the Apple iPhone and Nintendo Switch, in addition to the growing automotive market, is highly significant. As of September 2012, ST Microelectronics had shipped 2 billion MEMS sensors that confirmed its leading global position in MEMS technology for consumer and portable application (Market Analyst IHS iSupply). By August 2020 this had grown significantly to 17 billion parts sold [5.3] with USD3.5 billion in revenue between January 2014 and August 2020 being associated with Inertial MEMS devices alone.

5. Sources to corroborate the impact

[5.1]. Arne Holst, Statista "Lifetime unit sales of the Nintendo Switch console worldwide from March 2017 to November 2020", 16th December 2020.
[5.2] S. O'Dea, Statista. Apple iPhone unit production volume by model from 2013 to 2017 Graph showing production numbers for iPhone 4, 4S, 5C and 5S. Dated 27th February 2020
[5.3] Davide Bruno, "ST has market leadership in MEMS & Sensors with wide & ready portfolio to address Automotive Applications" corroborating ST Microelectronics' involvement in developing driver assistance systems and sales of 17 billion parts. Dated 10th September 2020
[5.4] Statement from Executive Vice President ST Microelectronics, 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 Nintendo and Apple. Dated 30th October 2019.
[5.5]. News Article, Research & Markets "Reverse Costing Analysis of the iPhone 5S MEMS Gyroscope STMicroelectronics 3x3mm". Shows 45% footprint reduction for iPhone 5. Dated 5th February 2014.
[5.6]. ST Microelectronics Press Release "Semiconductor Solutions from STMicroelectronics Selected by Nintendo for Nintendo Switch". Corroborates the evolution of the relationship between ST Microelectronics and Nintendo the use of STMicroelectronics inertial devices in the Switch. Dated 13th March 2017.
[5.7]. Arne Holst, Statista "*Console unit sales of the Nintendo Wii and Wii U from 2007 to 2018*" 4th January 2021. Corroborates sales figures for the Nintendo Wii and Wii U for 2014 and 2017.