UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

Intelligent Sensor Microsystems

by

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CONTENTS

1. Synopsis of achievements

Intelligent Sensor Microsystems

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The papers constituting this submission were co-authored by the following students, research fellows, academic colleagues or industrial and clinical collaborators. Some individuals fall into more than one category. I have actively contributed to all of the papers listed as either generator of the idea, experimenter and analyst, project leader or co-writer as noted for each publication. All citation numbers are taken from Google Scholar.

Supervised Undergraduate/postgraduate and PhD Students: Alhoseyni Almodarresi Yasin SMT, Ash J, Cotton DPJ, Esmaeili K, Frood AJ, Gleeson R, Glynne-Jones P, Grabham NJ, Henderson NJ, Jafaripanah M, James EP, Jellard SCJ, Ko VTK, Kok SL, Lau S-P, Leach GR, Liu J, Manla G, Mathioudakis I, Merrett GV, Monkronthing S, Naylor AJ, Page SF, Papakostas T, Shaban M, Shi WJ, Sion RP, Stuttle M, Torah RN, Tronco Jurado U, Weddell AS.

Supervised Visitors and Research Fellows: Aoyagi M, Bashir I, Beeby SP, Boltryk P, Chambers P, Chmiel FP, Cranny AWJ, Dargie PG, Dolia AN, Duckworth C, El-Hami M, Ensell G, Fraigi LB, Grabham NJ, Hamidon MN, Lambert R, Harris NR, Hoffman F-M, Karatzas D, Koch M, Koukharenko E, Li X, Mass R, Mazomenos EB, Merrett GV, Metcalf CD, Peters C, Pirzada P, Skarda V, Scivier PK, Taner AH, Thorbjornsen B, Townsend RJ, Torah RN, Tudor MJ, Wei, Y, Xun L, Weddell AS, Zaghari B.

Academic Co-authors: Adams J, Al-Hashimi B, Atkinson JK, Augousti AT, Bagnall DM, Beeby SP, Boden SA, Boniface MJ, Brignell JE, Brown AD, Brunnschweiler A, Bull D, Burridge JH, Chad JE, Chappell PH, Chorti A, WT Coakley, Dorey RA, Dyakowski T, Evans AGR, Fazi FM, Gabriel S, Gardner JW, Hale JM, Harris CJ, Harris NR, Hartel P, Harvey T, Hawkes JJ, Hill M, Holland KR, James C, Jaworski A, Jones BE, Kraft M, Lutman ML, Merrett GV, Metcalf CD, Mihaylova L, Nandhakumar I, Pu S-H, Rakowski RT, Reeve JS, Ross JN, Spencer D, Swabey M, Turner JD, Veldhuis R, Vidic M, Wang L, Wei Y, Weddell AS, Whatmore RW, Wilde A, Wood RJK, Yang K, Zhu D.

Industrial and Clinical Collaborators and Co-authors: Akerman H, Azor M, Badger J, Bakopoulos CP, Binhack M, Buff W, TWV Daniels, Grocott M, Hallett G, Hayward N, Holford KM, Holweger W, Kulkarni C, Kiuber M, Knight M, Krispel F, Levett D, O'Donnell T, Otto J, Rayat G, Roy S, Saha T, Schiedt B, Speed J, Trautmann C.

Since obtaining my PhD in 1988, I have conducted research in the area of *Intelligent Sensor Microsystems*. The field is broad and I have hence broken it down into five distinct areas, some of which overlap to a greater or lesser extent. The research areas are:

1. Thick-film sensors, materials and devices
2. Intelligent instrumentation
3. Microsystems technologies
4. Energy harvesting
5. Medical sensors

Some examples of highlights of my research career include being awarded the 2009 **Callendar Silver Medal**, awarded by the Institute of Measurement and Control for my *'outstanding contribution to the art of instruments or measurement*', being awarded over **£10M of research funding** as PI/Co-I, publishing a review paper with over **3670** citations, author/co-author or editor of **15 books**, named inventor on **11 patents**, and supervising over 30 PhD students through to completion. I have published more than **300** papers, of which 227 have been selected for this award. My Google Scholar profile shows a total citation count exceeding **15,000**, with a h-index of 50 and i10-index of 179. I am the **co-founder** and former Director of the University spin-out company Perpetuum Ltd., which was sold to Hitachi Rail in 2021.

1. Thick-film sensors, materials and devices

My first paper as a post-doctoral researcher was published with a visiting Argentinian researcher on the subject of thick-film strain gauges on insulated stainless-steel substrates and followed on from my PhD research (awarded in 1988) [1]. My work in this area was also featured at one of the first major microsystems conferences (Transducers ’89) held in Switzerland in 1989 [2]. I was awarded the International Society for Hybrid Electronics Educational prize in 1989 for a paper describing my own, original work on how thick-film strain gauges can be printed and characterised onto stainless steel substrates [3]. This work also led to the development of a novel form of a weighing sensor (load cell), which is discussed in [4,6]. The device can compensate for off-axis loads, thereby eliminating the issue of load eccentricity in weighing systems. The research also led to collaboration with industry, which resulted in a publication describing the use of my research into thick-film piezoresistors for use in automotive pressure sensors [5]. In the summer of 1991, I developed a successful formulation for a screen printable piezoelectric material. This was to become a key element in many future published applications from my research team. Examples of the use of this material are described in [8,9,17,21,24]. A key paper in 1993 [8] describes, for the first time, how a printed thick-film piezoelectric material can be used as the basis of an acoustic wave sensor. This is also described in more detail in reference [9]. The work led to an EPSRC grant to continue the research. A journal paper published in 1995 describes my early work on using thick-film technology in resonant sensors [10]. In 1997, Internal collaboration with academic colleagues and PhD students in other research groups in ECS, led to the publication of a unique type of micro-fluidic pump with a thick-film piezoelectric actuator [12,14,15].

In 1996, I was invited to be the lead author of a review paper, which also contains my own novel research, on thick-film sensors [13]. It also proposed a new field of combining thick-film technology with silicon. This paper has been cited 354 times. In 1996, I received EPSRC funding as Principal Investigator (PI) for the project *Thick-film acoustic wave sensors,* which investigated the development of novel types of thick-film acoustic wave sensing structures. These are described in references [17,21,24]. In 1997, further internal collaboration at the University of Southampton led to further advancements in the performance of my thick-film piezoelectric material formulation that I developed in 1991, and has resulted in many variations in the formulation, characterisation techniques, sensors and actuators as described in references [16,19,20,73,83,89,90,95,115,123,142,143,190]. In 1998, the formulation of the thick-film piezoelectric material was successfully modified to produce a polymer, flexible version [22,31,34,41,44,48]. One application of this sensing material was a sensor for use in a novel type of biometric system, which was able to detect an individual by the way in which they type their PIN number [60,62,66,67]. Following on from the successful fabrication of the silicon micropump, further research was conducted into methods of combining silicon and thick-film technologies [25,26,27,32,38,42,47,49]. The research was funded by EPSRC under their Realising Our Potential Awards (ROPA) (*Combined thick-film/silicon micromachined structures*), with myself as PI. In 1999, I was PI of an EPSRC project entitled *Self-Powered Microsystems*, which aimed to study how microsensors could be powered and their signals extracted without the use of wires. The project investigated the use of our screen printable piezoelectric material as the source of a vibration-powered generator [37,55]. The research is also summarised in publication [58], of which I was lead author and which has 285 citations. During this period, electromagnetic energy harvesting systems were also studied, and this helped to establish Southampton as one of the pioneers in the field energy harvesting and also led to the formation of Perpetuum Ltd (see research area 4, *Energy Harvesting*). In 2000, I also collaborated with Cranfield University as a Co-I on the EPSRC project *Ferroelectric composite sol-gel fabrication* in which we developed combinations of thick-film piezoelectric materials based on screen printing and sol-gel deposition methods [76,101]

In 2001, I was PI on an EPSRC project entitled *Thick-Film Magnetostrictive Actuators for MEMS.* The project led to the formulation of an additional, novel type of thick-film material, based on the magnetostrictive properties of Terfenol [59,64,71,79,86], which we had previously published in 2000 [39]. The project included collaboration with a spin-out company from The University of Hull (Newlands Research Ltd.) who subsequently invited me to join their Board as a non-executive Director from 2001 - 2003. In 2001, I hosted a Visiting Researcher from Yamagata University, Japan and we developed the first example of a thick-film, multi-degree-of-freedom ultrasonic motor [61]. This publication has been cited 122 times.

Also in 2001, I was a Co-I on an EPSRC project called *Multi-modal and self-cleaning instrumentation for the oil and gas industry using thick-film materials*, which included Newcastle and Manchester Universities [75,78,93,99,109,110,128,135]. The thick-film piezoelectric material was used as a novel type of ultrasonic sensor to detect particle flow in oil and gas pipelines and was the subject of a granted patent, with myself as a named inventor [2003, 2005 (see CV)].

The third major EPSRC funded project (as Southampton PI) in 2001 was an EPSRC Faraday Partnership between Southampton and Brunel, *Resonant microsensor*

modules for measurement of physical quantities (REMISE). There were several industrial partners including Corus, Rolls Royce as well as a variety of SMEs. The project was based around thick-film piezoelectrics on insulated metal substrates, which were configured in a resonant structure known as a triple beam tuning fork. The project led to a patent (2003 (see CV)], with myself as a named inventor, as well as a number of publications [77,80,82,97,111]. After the project was completed in 2004, Brunel formed a spin-out company (ForceSensys Ltd.) to exploit this technology.

My fourth EPSRC project, as PI, in 2001 was *Micromachined Ultrasonic Filter with Thick-Film Piezoelectric Drive for Microfluidic Applications*. This was a collaboration between ECS and Mechanical Engineering at Southampton and also Biosciences at Cardiff University. The concept was to extend our previous work on combined thick-film/silicon structures to develop a microengineered silicon ultrasonic filter, capable of separating small (1 micron diameter) particles within a fluid. The ultrasonic actuator was based on a screen-printed piezoelectric material fabricated onto a silicon diaphragm [124,131], the latter paper having attracted 112 citations. Additional publications resulting from this project will be covered in section 3 (*Microsystems Technologies*).

In 2003, I was PI on an EPSRC project called *Thick-Film Sensors for Prosthetic Hands*. The aim of this was to produce a state-of-the-art prosthetic hand with advanced sensing technologies integrated into the structure and based on a variety of thick-film sensors, including strain gauges, piezoelectric slip sensors and temperature sensors. The research led to worldwide publicity for the University, with coverage on television including BBC, ITV and Channel 4, as well as high-quality publications [94,118,122,140,144,146], one of which [144] I presented as an invited paper at the 2007 *Transducers* '07 Conference. Paper [140] has attracted 158 citations.

For many years, I was interested in producing thick-film mechanical sensors that were not fixed rigid on the substrate. In 2009, this was achieved through the development of a new technique to fabricate free-standing thick-film piezoelectric structures, which used carbon films as a sacrificial layer. This was achieved in conjunction with one of my PhD students. The devices are similar in nature to those produce by surface micromachining of silicon. The devices were fabricated, characterised and also configured as a novel type of piezoelectric energy harvester [155,156,157,172,175].

In 2013, I was a Co-I on a BBSRC project entitled *Robust, Ion-Selective Thick-Film Sensors for Long-Term Field Deployment*, which produced thick-film sensors for agricultural monitoring [194,197]. These were deployed in a field trial in Australia conducted by a colleague in ECS.

2. Intelligent instrumentation

The phrase *Intelligent Instrumentation* is defined as being hardware and software sensor systems, which can adapt their response in accordance with external conditions. Also within the definition is the nature of the communication methods by which the sensor signal is transmitted (i.e. a simple analogue signal, wired or wireless network). This definition was proposed in a monograph that I co-authored in 1994 (See reference later in the paragraph) and has been widely adopted by the research community. My research into intelligent instrumentation began in 1991, when I was a Co-I on a SERC (now EPSRC) project entitled *ASICs in smart sensors*. The aim of this project was to develop a core number of elements in an Application

Specific Integrated Circuit (ASIC) for intelligent sensors [18]. In 1993, one of my PhD students assessed a number of different software techniques to correct the time response of load cells [7]. The research was summarised through the publication of a monograph in 1994 (see CV *Books*), which was co-authored with John Brignell who was a pioneer in the field. The monograph has gained 172 citations.

In 1996, research conducted with another PhD student demonstrated how virtual instrumentation can reduce problems of design complexity in the design of intelligent sensor systems [11]. Software techniques, based on neural networks, to improve response times of load cells were developed with a PhD student 1999 [27,29]. A spin-off from this research included a calendar conversion process for real-time systems [96], which allows switching between the Gregorian and Khayyami calendars. In 2000, I co-authored a publication that describes a way of linearising the output of a silicon pressure sensor [36] and also a method of exciting micromachined silicon resonators [45,50]. Self-testing techniques for micromachined accelerometers were developed in 2001 [52,65]. Software techniques for the pressure sensing biometric described in section 1, were produced in 2002 [62,66]. In 2003, the problem of compensating the load cell was revisited using a wholly analogue technique and no software [74,103,104,120].

In 2003, I was the Co-PI on two Defence Technology Centre projects in the area of intelligent sensors. One was entitled *Multi-Sensor Active Management* and the other *Optimal Signal Extraction and Sensor Modelling Algorithms* [102,105,106,113,114,127,130, 136,138,141,145,184]. Publication [105] was a plenary paper, which I presented at Nanotech 2005, Anaheim, USA.

In 2006, I was the PI on an EPSRC Platform Grant called *New Directions for Intelligent Sensors*. One of the main research themes of the grant was that of wireless sensor networks. Several co-authored publications were produced at a time when the subject area was just beginning to emerge in the wider research community. Of particular note here is the combination of wireless sensor network applied to energy harvesting systems [107,112,149,152,153,160,163,166,170 168,169,170,177,186,187,191], which has now become a major topic area at international conferences and in journals. Biometric sensors were assessed as a work package in this grant and one example was the use of thick-film pressure sensors embedded into keypads, so that PIN numbers can be tied to an individual even if someone else knows the number [150]. This research is based on findings from the First World War, when it was discovered that individual Morse code operators could be identified by their tapping signatures.

In 2007, I pursued my interest in biometric sensors as a Co-I on the EPSRC project *Otoacoustic Emission-Based Biometric Systems,* which aimed to develop a system for identifying individuals by the otoacoustic emissions produced within the inner ear [173,180,183]. Research undertaken in 2012 by a PhD student that I co-supervised, led to a methodology for adaptive street lighting that can be used within an urban environment to save power when no people or cars are within the vicinity of a streetlight. The system is based on a wireless sensor network [195,202]. The research produced a simulator for modelling the system, which has been widely cited [196] (111 times).

In 2016, I was a Co-I on an EU Clean Sky 2 project entitled *Integrated Intelligent Bearing Systems (I2BS),* whose aim was to develop a smart bearing for aircraft that had the ability to monitor its health condition. My contribution to the project was in the area of the wireless sensors and energy harvesting techniques [212, 217,225].

3. Microsystems technologies

Microsystems, or MicroElectroMechanical Systems (MEMS) has a broad definition. In the context of my research on this area, it largely covers processing techniques and the use of novel materials in addition the fabrication of the complete system. The first example includes work undertaken by a third-year undergraduate project student in 1999 to develop a capacitive pressure sensing system [25]. A further paper discusses how diffused silicon piezoresistors can be used to detect surface strains in a silicon resonator structure [33]. Research on the intelligent load cell (in section 2) resulted in the development of a complete integrated circuit design, based on current mirrors [74], which form a wholly analogue hardware implementation of the frequency response correction methods that we had previously implemented in software. The research emerging from the EPSRC project on micromachined ultrasonic separator resulted in publications [65,67,72,81,91,92,119,122]. Reference [81] has attracted 240 citations and paper [92] has 156 citations. I took on the role as PI on an EU (ESPRIT) project called *Wireless Monitoring Online of Strain and Temperature* (*WIREGONE*) in 2001, which resulted in the publication of the development of a wireless temperature sensor fabricated onto a high-temperature (>600C) gallium orthophosphate substrate [136]. The design of the silicon ultrasonic separator (from EPSRC project *Micromachined ultrasonic filter with thick-film piezoelectric drive for microfluidic applications*), from a microsystems perspective, is described in publication [137]. The EPSRC project *Highly-Efficient Thermoelectric Power Harvesting* in 2006, of which I was PI, brought together microsystems technologies and energy harvesting (see section 4). The project was a collaboration between ECS and the School of Chemistry and led to further joint supervision of PhD students in the following years. Examples of the published work relating to the microsystems fabrication aspects include publications [176,179,182,188,192,201,205,207]. In 2007, I was a Co-I on a European Space Agency (ESA) feasibility project, *Advanced Injectors For Chemical Rockets Inspired by Inkjet Printing Technology*. The aim of this project was to investigate, and propose, a variety of designs for using MEMS-based printer heads as the basis of a propulsion mechanism for rocket engines [162]. A paper published in 2013 discusses the fabrication of a MEMS-based voltage step-up converter [189], which resulted from joint supervision of a PhD student. The concept of using piezoelectric arrays, driven by multi-level digital signals (sometimes referred to as digital loudspeakers) was investigated by one of my PhD students in 2012 and resulted in publications [193, 203]. This work led to a collaboration with the Institute for Sound and Vibration Research (ISVR) and resulted in a project funded by Huawei (*MEMS Transducer Arrays for Compound Super-Transducers*) to take forward the concepts of the digital loudspeaker. I was Co-I on this project, which led to publication [223].

4. Energy harvesting

My research in the area of energy harvesting began in 1997 when I began to investigate the application of the thick-film piezoelectric material, which I developed in 1991, as a means of powering sensors by using ambient vibrations. In 1999, I was awarded an EPSRC project (as PI) entitled *Self-Powered Microsystems*, which was one of the first UK Research Council projects in the area of energy harvesting. In order to assess the performance of the piezoelectric harvesters, a comparison was made

against electromagnetic generators. An initial publication emerged in 2000 [35] and the concept of an electromagnetic generator was presented at the Eurosensors conference in 2000 [43]. Its application to powering microsystems was presented at *International Symposium on Smart Structures and Microsystems* in the same year [46]. The research was published in the journal *Sensors and Actuators* in 2001 [51] and has now been cited 625 times and is hence regarded as a key paper in the field of vibration energy harvesting using electromagnetics. Wireless methods for signal extraction of vibration-powered systems are described in [53]. A paper describing the performance of piezoelectric vibration-powered harvesters was also published in 2001 [54]. This paper has 579 citations and is hence a key paper in the field of piezoelectric energy harvesting. The research on electromagnetic and piezoelectric generators was described in a paper published in 2001 [56], which was given a Highly Commended Award by the Literati Club in 2002 and has attracted 150 citations. A further paper on the subject of piezoelectric harvesters was presented at *Eurosensors/Transducers 2001* [57] and attracted 95 citations. The electromagnetic generator was further discussed in [63,68,70] leading to two highly cited papers in 2004 [87,88]. The former being cited 198 times and the latter 1048 times. In 2003, owing to the success of the research into electromagnetic harvesters and the potential for commercial exploitation, several patents were filed (see CV patents [3,7,8,9,10]). In 2004, Perpetuum Ltd. (www.perpetuum.com) was spun-out from the University with myself as a Director and Co-Founder. The company attracted around £10M of investment funds and established offices in the USA and the Far East and was sold to Hitachi Rail in 2021. At the time of sale, the company was firmly established as a global leader in vibration energy harvesting systems and had 75 employees, making it one of the largest companies to spin-out from the University of Southampton.

In 2004, the energy harvesting work was continued through the EU project *Vibration Energy Scavenging (VIBES)*, of which I was a Co-I and resulted in publications [116,117, 134,139]. The latter two papers each attracting 115 citations. In 2006, I co-wrote a review paper on energy harvesting for microsystems [132], which has had 3671 citations and has been downloaded **43,656** times from the *Measurement Science and Technology* website, making it one of the most highly cited journal papers in the field and is stated on the MST, Dimensions web page as being "…**extremely highly cited** and has received approximately **825 times** more citations than average.". An application of the electromagnetic generator for powering sensors nodes from airflow is described in publication [185,198]. The challenge of applying energy harvesting methods for powering sensor nodes is discussed in publications [151,154,164,]. These are based on research undertaken as part of the EPSRC project *Next Generation Energy Harvesting Electronics: A Holistic Approach*, of which I was a Co-I. This project was a collaboration between Southampton, Newcastle, Imperial College and Bristol Universities. As part of this project, human-powered generation was studied and led to publication [199], which investigated the location and position of generators on the human body to allow maximum power output, with minimal obstruction to the individual. Research with a PhD student in 2012 into the concept of generating power from a vehicle wheel using piezoelectric materials [181].

The use of temperature differences for powering sensor nodes became an area of interest in 2006 via the EPSRC project mentioned in section 3. Papers arising from the project include publications [158,159,161,211]. More recent research (from 2018 onwards) in the area of energy harvesting, with PhD students, has assessed the feasibility of using piezoelectric harvesters to power sensor nodes from rainfall

[214,216,219] and also exploiting the triboelectric effect in dissimilar dielectrics to power nodes from the impact of wave motion on the generators [215,218,221]. In 2022, I co-authored an overview paper on the subject of energy harvesting in the transport industry [227].

5. Medical sensors

My interest in the area of medical sensors arose from the research within the EPSRC project *Thick-Film Sensors for Prosthetic Hands* in 2003. In addition to the publication on thick-film sensors for the hand describe in section 2, further research included studies on the motors and also control strategies for the multi-degree-of-freedom prosthetic [147,148]. Additional research focussed on the detection of object slippage in the hand and also investigations on the ability of the hand to monitor the texture of gripped objects [174,200,204,209,211]. Collaboration with the School of Health Sciences and physiotherapists at University Hospital Southampton (UHS) in 2009 led to a publication describing fabric-based, wearable strain sensors [165]. As a result of my son rupturing his Anterior Cruciate Ligament (ACL) in his knee and requiring surgery, I formed a collaboration with knee surgeons and physiotherapists and UHS. Patients recovering from knee surgery are often encouraged to place a defined percentage of their body weight on the affected limb. The main problem is that most patients have no idea how to gauge 20%, 50% or 75% of their weight. Hence, the need for an instrumented crutch was established, which can give audio and visual feedback for a pre-defined percentage of body weight. The research attracted broad publicity on the BBC and ITV news networks and is described in publications [171,178].

I held the role of Head of the School of Electronics and Computer Science from 2011 to 2015 and made the decision that medical sensors would be the focus of my research moving forward. Since 2018, I have been a Co-Director of the ECS Centre for Healthcare Technologies (CHT) and have built up a strong network of clinical collaborators. I co-authored a paper with an MSc student on the subject of Smart Homes for the elderly [210]. In 2017, I published a paper describing for the first time how a proximity sensor, known as a capaciflector, can be used as a respiration sensor [206]. Having spoken to anaesthetists at UHS, it became apparent that there was clear medical interest in this concept as breathing rates in patients are routinely measured via manual counting of chest movement. Respiration rate is the only physiological parameter not measured continuously or with an instrument on patients admitted to hospital. In 2019, we conducted clinical trials of the device on 50 patients (https://clinicaltrials.gov/ct2/show/NCT03832205) and compared the results against the gold standard pneumotachometer. The results are discussed in publication [226]. The device is now the subject of an NIHR i4i project (*Continuous Respiration Monitoring Using a Novel, Wearable Capaciflector Sensor for Early Detection of Distress, Enabling Quicker Intervention for Improved Patient Outcomes*), which was awarded in 2021 with myself as the PI. We have recently trademarked the name *PneumoRator* to refer to the device. Collaboration with the Accident and Emergency Department at UHS and colleagues within ECS, resulted in the award of an Alan Turing Institute project (*TriagED - Decision Support Algorithms for Emergency Departments*) in 2020 [220,222]. In addition to being the PI, I was awarded a Turing Fellowship with the project.

The work presented in this submission has not been submitted for a degree at the University of Southampton or any other university.

2. Selected publications on which DSc submission is based

(* denotes the 10 most significant papers)

(1) Fraigi LB, **White NM**, Atkinson JK and Brignell JE, Sensores de pelicula gruesa piezorresistivos, 1989, *Mundo Electronico*, 80-86 (in Spanish)
(NMW conceived idea, analysed data, and co-wrote article {in English})

(2) Atkinson JK, Cranny AWJ, Fraigi LB and **White NM**, Thick-film sensors: Application and characterisation, *Proceedings of Transducers '89*, *Montreux, Switzerland*, 1989
(NMW conducted experimental work, co-wrote article)

(3) **White NM**, Assessment of thick-film piezoresistors on insulated steel substrates, *Hybrid Circuits,* 1989, **20**, 23-27
(NMW single author. This paper won the ISHM Educational Prize in 1989)

(4) **White NM** and Brignell JE, A planar, thick-film load cell, *Proceedings of Eurosensors IV, Karlsruhe, Germany,* 1990
(NMW co-wrote paper, conducted experimental work)

(5) Holford KM, Bakopoulos CP and **White NM**, The development of a high pressure, thick-film sensor, *Proc I.Mech.E Mechatronics conference, Robinson College, Cambridge, 11-13 September*, 1990, 47-59
(NMW experimental work, data analysis, co-wrote paper)

(6) **White NM** and Brignell JE, A planar thick-film load cell, *Sensors and Actuators*, 1991, **26**(1/3), 313-319
(NMW experimental work, analysis and co-wrote paper)

(7) Shi WJ, **White NM** and Brignell JE, Adaptive filters in load cell response correction, *Sensors and Actuators A*, 1993, **37-38**, 280-285
(NMW PhD supervisor, experimental analysis and co-wrote paper)

(8) **White NM** and Ko VTK, Thick-film acoustic wave sensor structure, *Electronics Letters*, 1993, **29**(20), 1807-1808
(NMW conceived idea, wrote paper, VTKK project student)

(9) **White NM** and Leach GR, Fabrication of a thick-film force sensor employing an ultrasonic oscillator, *IEE Proc. Science, Measurement and Technology*, 1995, **142**(3), 249-254
(NMW conceived idea, wrote paper, GRL project student)

(10) **White NM** and Brignell JE, Excitation of thick-film resonant sensor structures, *IEE Proc. Science, Measurement and Technology*, 1995, **142**(3), 244-248
(NMW experimental work and co-wrote paper)

(11) Taner AH and White NM, Virtual instrumentation: A solution to the problem of design complexity in intelligent instrumentation, 1996, *Measurement and Control*, 29, 165-171 (**Cited 62 times**)
(NMW data analysis, co-wrote paper)

(12) Koch M, Harris NR, Mass R, Evans AGR, **White NM** and Brunnschweiler A, A novel micropump design with thick-film piezoelectric actuation, *Measurement Science and Technology*, 1997, **8**(1), 49-57 (**cited 158 times**)
(NMW data analysis, co-wrote paper)

*****(13) **White NM** and Turner JD, Thick-film sensors: Past, present and future, (Invited review paper), 1997, *Measurement Science and Technology*, **8**, 1-20 (**cited 354 times**)
(NMW co-wrote paper, device fabrication of some of the sensors described)

(14) Maas R, Koch M, Harris NR, **White NM** and Evans AGR, Thick-film printing of PZT onto silicon, 1997, *Materials Letters*, **31**, 109-112 (**cited 113 times**)
(NMW contributed to sensor design, co-wrote paper)

(15) Koch M, Harris N, Evans AGR, **White NM** and Brunnschweiler A,
A novel micromachined pump based on thick-film piezoelectric actuation
Proceedings Transducers 97, Chicago, USA, 1997, 353-356
(NMW contributed to sensor design, co-wrote paper)

(16) Dargie PG, Sion RP, Atkinson JK and **White NM**, An investigation of the effect of binder type, concentration and poling conditions upon the characteristics of screen printed piezoelectric materials, *Proceedings Eurosensors XI*, Poland, 1997, **3**, 1287-1289
(NMW conceived idea, experimental work, co-wrote paper)

(17) Harris NR and **White NM**, Hybrid delay line sensors, *Sensors and their Applications VIII*, Augousti AT and White NM (eds), IOP Publishing, Bristol, 1997, ISBN 07503 04219, 213-218
(NMW conceived idea, contributed to sensor design, co-wrote paper)

(18) Scivier PK, **White NM**, Brignell JE, Gardner JW and Vidic M, Pulsed current analogue CMOS ASIC for excitation of polymer-based gas sensors, Eurosensors XI, Poland, 1997
(NMW contributed to design, co-wrote paper)

(19*)* Dargie PG, Harris NR, **White NM**, Atkinson JK and Sion RP, Formulation of a screen printable piezoelectric thick-film, *Sensors and their Applications VIII*, AT Augousti and NM White (eds), IOP Publishing, Bristol, 1997, ISBN 07503 04219, 201-206
(NMW conceived idea, contributed to experimental work, co-wrote paper)

(20) Dargie P, Sion R, Atkinson JK and **White NM**, An investigation of the effect of poling conditions on the characteristics of screen printed piezoceramics, 1998, *Microelectronics International*, **15**(2), 6-10
(NMW contributed to experimental work, co-wrote paper)

(21) Harris NR and **White NM**, Practical Properties of an elastic wave sensor structure, 1998, *Proceedings of Eurosensors XII*, **1**, ISBN 07503 059591998, 445-448
(NMW contributed to experimental work, co-wrote paper)

(22) Papakostas T, Harris NR, Beeby SP and **White NM,** Piezoelectric thick-film polymer pastes, 1998, Proceedings of Eurosensors XII, **1**, ISBN 07503 05959pp 461-464
(NMW supervised PhD student (TP), contributed to experimental work, co-wrote paper)

*****(23) Koch M, Harris NR, Evans AGR, **White NM** and Brunnschweiler A, A novel micromachined pump based on thick-film piezoelectric actuation, 1998, *Sensors and Actuators A*, **70**(1-2), 98- 103 (**Cited 287 times**)
(NMW contributed to sensor design, co-wrote paper)

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(226) Hayward N, Shaban M, Badger J, Jones I, Wei Y, Spencer D, Isichei S, Knight M, Otto J, Rayat G, Levett D, Grocott M, Akerman H and **White NM**, 2022, A capaciflector provides continuous and accurate respiratory rate monitoring for patients at rest and during exercise, *Journal of Clinical Monitoring and Computing*, doi: 10.1007/s10877-021-00798-7.
(NMW conceived idea, contributed towards design and ethics for clinical trial, co-wrote paper)

(227) **White NM** and Zaghari B, 2022, Energy harvesting: an overview of techniques for use within the transport industry, *IEEE Electrical Insulation Magazine*, 38 (3) 24-32.
(NMW co-wrote paper, equal contribution)

3. CURRICULUM VITAE

Neil M. White BSc, PhD, CEng, CPhys, FIET, FInstP, SMIEE

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Professional Career

1988 - 1990	**Research Fellow** University of Southampton Institute of Transducer Technology (USITT), Highfield, Southampton.
1990 - 1999	**Lecturer** (School of Electronics and Computer Science, University of Southampton)
1999 - 2000	**Senior Lecturer**
2000 - 2002	**Reader**
2002 - present	**Professor of Intelligent Sensor Systems and**
2007 - 2011	**Head of Electronic Systems and Devices Group**
2008 - 2011	**Deputy Head of School (Enterprise)**
2011 – 2015	**Head of the School of Electronics and Computer Science**
2018 - present	**Director of the Centre for Health Technologies** (in ECS)
2019 – present	**Visiting Professor** (School of Science and Technology, Nottingham Trent University)

Citation Index (Google Scholar)

Citations:	15,372 Highest citations per year: 1060 (2014)
h-index:	50
i10-index:	179

Awards/Prizes

- Winner of the 1989 ISHM-UK (International Society for Hybrid Microelectronics, UK) Educational Prize.
- Highly Commended award from the Literati Club for an article on thick-film piezoelectrics in Microelectronics International, 1998, **15**(2)
- Highly Commended award from the Literati Club for an article on Self-powered systems, Sensor Review, 2001, **21**(2)
- Winner of the Callendar Medal, 2009, Institute of Measurement and Control

Professional qualifications

Chartered Engineer	(Registered number 444317)
Fellow of the IET	(Registered number 20085887)
Chartered Physicist	(Registered number 61956)
Fellow of the IOP	(Registered number 61956)
Senior Member of the IEEE	(Registered number 41378614)
Fellow of the HEA	(Registered number 14416)

Committee membership etc.

- Measurements and Instruments Committee, professional group E1, IEE. 1992-1998
- Honorary Secretary of the Instrument Science and Technology (ISAT) Group, Institute of Physics. (1994-1996)
- Associate Editor for the IEE *Electronics and Communications Journal*.
- Member of the Organising Committee for *Sensors and Their Applications VII*, Dublin 1995.
- Conference Organiser for the ISAT day at IOP Annual Congress 1996.
- Member of the Organising Committee for *Sensors and Their Applications VIII*, Glasgow 1997.
- Co-editor of the Proceedings of *S&A VIII* September 1997
- Guest Editor for a special issue on 'Thick-Film Sensors'*, Measurement Science and Technology,* 1997*.*
- Editor of the Proceedings of Eurosensors XII, Southampton 1998.
- Member of the Organising Committee for Eurosensors XII, 1998.
- Chairman of Instrument Science and Technology Group (ISAT), Institute of Physics, September 1996 - 1999.
- Member of the local organising committee for MicroMechanics Europe 1997
- Guest Academic Editor for *Sensor Review* Vol. 17 No. 2 June 1997.
- Member of Editorial Board of *Sensor Review*, January 1998.
- Chairman of *Sensors and their Application X*, Cardiff 1999
- Member of EPSRC Peer Review College (2000-)
- Guest Academic Editor for *Sensor Review* Vol. 21 No.1 January 2001
- Member of the Editorial Board of the *Journal of Materials Science: Materials in Electronics* (2003-)
- Series Editor *MicroElectroMechanical Systems (MEMS)* series, Artech House (2006 -)
- Honorary Editor, *Mehran University Research Journal of Engineering and Technology*
- Steering Committee member, IMTIC, 2008, Jamshoro, Pakistan
- Member of the Outstanding Paper Committee Transducers 2009, Denver, USA
- Member of the IWPMA 2011 International Advisory Committee, Roanoke, Virginia USA, 7-11th August 2011
- Steering Committee member, IMTIC, 2011, Jamshoro, Pakistan
- I am also a referee for a number of learned journals, EPSRC, EU and other overseas research proposals.

- Member of the International Programme Committee for Eurosensors (2012 -)
- Member of the International Programme Committee for Transducers (2012 -)
- Member of the Steering Committee of WSN4DC'13, 2013, Pakistan (2013)
- Reviewer for Professorial posts at University of Oulu (Finland), Nottingham Trent University, University of Malta, Macquarie University (Australia), University of Cyprus.

Books

(1) Brignell JE and **White NM**, *Intelligent Sensor Systems,* Institute of Physics Publishing, Bristol, April 1994, ISBN: 07503 02976

(2) Brignell JE and **White NM**, *Intelligent Sensor Systems (revised edition)* Institute of Physics Publishing, Bristol, June 1996, ISBN 07503 03896 (**Cited 172 times**)

(3) **White NM**, Chapter 1 *Thick-film technology,* in "Thick-film sensors", M. Prudenziati (ed), Elsevier, ISBN 04448 97232, August 1994

(4) Brignell JE and **White NM**, Chapter 7 *Advances in intelligent sensors,* in "Adaptronics and smart structures - basics, materials, design and applications", H. Janocha (ed), Springer, ISBN 61484-2, 1999

(5) Augousti AT and **White NM** (eds), *Sensors and their Applications VIII* IOP Publishing, Bristol, September 1997 ISBN 07503 04219

(6) **White NM** (ed), *Eurosensors XII incorporating Sensors and their applications IX,* Vols. 1 and 2, IOP Publishing September, 1998, ISBN 07503 05363

(7) **White NM** and Augousti AT (eds), *Sensors and their Applications X* IOP Publishing, September 1999, ISBN 07503 06254

(8) **White NM**, Beeby SP, Kraft M and Ensell GJ (eds) *MEMS: Mechanical Sensors,* Artech House, 2004, ISBN 15805 35364. (**Cited 727 times**)

(9) **White NM**, Beeby SP and Grabham NJ, Chapter 4, *Thick-film piezoelectric and magnetostrictive devices*, in "Electroceramic-based MEMS", N Setter (ed), Kluwer, ISBN 038723310-5, 2005

(10) **White NM**, Chapter 30, *Thick-films,* in "Springer Handbook of Electronics and Photonic Materials", S Kasap and P Capper (eds), Springer, ISBN 038726059-5, 2006

(11) **White NM** and Boltryk P, Chapter 7.1, *Advances in Intelligent Sensors*, in "Adaptronics and Smart Structures" (2nd edition), H Janocha (ed), Springer, ISBN 9783540 719656, 2008

(12) Beeby SP and **White NM** (eds), *Energy Harvesting for Autonomous Systems*, Artech House 2010, ISBN 9781596 937185 (**Cited 447 times**)

(13) Kraft M and **White NM** (eds), *MEMS for automotive and aerospace applications,* Woodhead Publishing 2013 ISBN 9780 85709 1185 (**cited 55 times**)

(14) Kok SL, **White NM** and Harris NR, *Free-standing piezoelectric cantilevers – Energy harvesting: Design, fabrication and characterisation*, LAP Lambert 2012, ISBN 384438 9695

(15) Nandhakumar I, **White NM** and Beeby SP (eds) *Thermoelectric materials and devices*, Royal Society of Chemistry 2016, ISBN 9781 78262 3236

Patents

(1) Papakostas TV and **White NM**, Polymer thick-film free-standing and free-supported structures, UK Patent Application 0025786.5, filed 20th October 2000
(2) Jones BE and **White NM**, *Metallic resonator,* UK Patent Application GB0302585·5, 2003
(3) **White NM**, Tudor MJ, Beeby SP, Harris NR and Glynne-Jones P *An electromagnetic device for converting mechanical vibrational energy into electrical energy,* GB 0320180.3, 2003
(4) Harris NR, Tudor MJ, SP Beeby and **White NM**, *A locking arrangement comprising two independent locking mechanisms*, UK Patent Application GB2380224, 2003
(5) Dyakowski T, Hale J, **White NM** and Jaworski A, *A sensing device,* UK Patent Application GB0320168.8, 2003
(6) Jaworski A, Hale J, Dyakowski T and **White NM**, *Pressure wave piezoelectric sensor*, US Patent Publication US 2007/0007861 A1, 27th August 2004
(7) **White NM**, Beeby SP, Harris NR and Tudor MJ, *A wafer-scale electromagnetic generator,* UK Patent Application GB0320180.3, 26th March 2004
(8) **White NM**, Beeby SP, Harris NR and Tudor MJ, *A multiple-mode, vibration-powered generator,* UK Patent Application GB305609, 26th March 2004
(9) Roberts S, Freeland R and **White NM**, *An electromechanical generator for converting mechanical vibration energy into electrical energy*, UK Patent Application GB2429337, 22nd February 2007
(10) Harris NR, Tudor MJ, **White NM**, Beeby SP and Glynne-Jones PG, *Electromagnetic device for converting mechanical vibrational energy into electrical energy and manufacture thereof*, US Patent Application Publication US 2007/0007827 A1, 11th January 2007
(11) Koukharenko E, Tudor MJ, **White NM**, Beeby SP, Nandhakumar I and Li X-H, *Highly efficient thermoelectric generator device using Lead Bismuth semiconducting nanowire structures, GB 0722968.5, 22 November 2007*