Institution: University of Bristol

Unit of Assessment: 15 – General Engineering

a. Overview

The Faculty of Engineering at the University of Bristol is a thriving centre of educational excellence and internationally-leading research. Since RAE2008, the Faculty's research grant income has risen steeply and consistently; in 2008/9 it was awarded **£10.2M** of new grants, which grew to **£19.1M** in 2011/12 and then **£40M** in the year 2012/13. This figure represents an increase of 250% in real terms since RAE2008 and hence the upwards financial trajectory presented for research spend in REF4 is set to continue. Research vitality has been enhanced over the REF period by the receipt of four Programme Grants and 27 competitively-awarded Fellowships.

Since 2008 the University has specifically prioritised centres for doctoral training to strengthen its postgraduate provision and, as a result, Bristol leads seven EPSRC doctoral training centres (the second highest number for any university) and of those the Faculty leads five and is partner in a further three, making it a premier venue for postgraduate training in national priority areas. The Faculty was awarded six further Centres for Doctoral Training (CDT) by EPSRC in November 2013 and, as a consequence of the successful pursuit of its strategy, PhD graduations will grow strongly from 2013/2014.

The Faculty has fostered major long-term relationships with industrial partners, using Preferred Partnerships, University Technology Centres, Framework Agreements and, on a larger scale still, through Catapult centres e.g. the £60M *National Composites Centre* (NCC). These partnerships provide pathways for impact as described in REF3a/b and include global engineering leaders such as Rolls-Royce, Airbus, Toshiba, EDF, AgustaWestland, GCHQ, GKN Aerospace and Vestas.

The Faculty's vision stresses the importance of fundamental engineering science, applied research and interdisciplinarity. Fundamental research that advances knowledge at the interface between Science and Engineering is exemplified by work on quantum information, resulting in three papers in *Science* along with seven papers in *Nature* journals. Interdisciplinary collaborations outside engineering include the *SPHERE* programme that unites 30 academics from 20 different electrical engineering, computer science and clinical science departments around a shared vision of research for society's major healthcare issues.

Modern engineering challenges are indeed increasingly interdisciplinary and hence the decision was made in 2009 to organise research at Faculty rather than Departmental level. This led to the formation of 18 Research Groups, 13 in this *General Engineering* (UoA 15) submission and 5 in a *Computer Science* (UoA 11) submission. The Groups are founded on the Faculty's academic strengths and the identification of five cross-cutting priority themes for growth, namely: *i* **Advanced Materials**, *ii* **Energy & Sustainability**, *iii* **Communications & Digital Media**, *iv* **Dynamics** and *v* **Bio-Engineering & Health**. The strategy to develop these themes in a sustainable way through staff appointments, postgraduate training and infrastructure investment is detailed in sections (c) and (d). *General Engineering* has grown to 121 FTE staff from the 104 in RAE2008 (submitted as separate *Applied Mathematics*, *Mechanical*, *Civil*, *Aerospace* and *Electrical Engineering* units).

b. Research strategy

Faculty Strategy

The Faculty maintains and strengthens the international reputation of its research through the underlying principles of:

- Attracting the best staff and students by means of the staff recruitment policies described in section (c) and by provision of appealing, vibrant and cohesive centres for doctoral training.
- Targeting strategic collaboration with industrial partners through a number of mechanisms but always with innovation-led companies that will create genuine and long-term synergies with the Faculty's vision.
- Collaborating with the best researchers wherever they may reside via a strong portfolio of EU projects and by strategic international activities including the Worldwide University Network as well as bilateral relationships with leading institutions in other continents.

The Faculty's five strategic priority areas are **Advanced Materials**, **Energy & Sustainability**, **Communications & Digital Media**, **Dynamics** and **Bio-Engineering & Health**. The 2008 RAE submissions proposed several key objectives in the development of these areas, including:

- The establishment of a cross-faculty ***Photonics*** group between Engineering and Physics, now widely-regarded as a world-leader in fields ranging from from terabit communications networks to quantum photonics.
- The formation of a single ***Dynamics and Control*** group drawn from existing activities in the Aerospace, Mechanical and Civil Departments to give critical mass and efficient utilisation of the world-class test facilities provided through the £25M *BLADE* investment in 2003. The Group was recognised with a £4.2M EPSRC Programme Grant on *Engineering Nonlinearity* in 2012.
- The development of **Bio-Engineering and Health** through appointments and investments has enabled the ***Robotics***, ***Applied Non-Linear Mathematics***, and ***Communications, Signals and Networks*** groups to expand activities in this area – the £3.8M *Sonotweezers* EPSRC Large Grant and the £12M *SPHERE* Interdisciplinary Research Centre (IRC) grant confirm Bristol as a major centre of healthcare technology.

The Faculty believes that the current themes will continue to flourish over the coming decade, with new opportunities for significant growth particularly expected in the areas of Health, Robotics, Quantum Information and Cybersecurity (the latter predominantly associated with UoA 11 activity).

Research Group Structure and Strategy

Within the Faculty's overall research strategy, each Group develops their own vision by identifying key intellectual challenges that address societal needs. They seek to maintain a sustainable and balanced portfolio of funding from UK research councils, the EU, industry and government. There is considerable interaction between Groups including numerous joint projects and they work together within the Faculty Research Committee to share good practice, co-ordinate shared resources, collectively allocate PhD funding and prioritise pump-priming research funding (see section (e)).

The following pages outline the activities, highlights and future directions of the 13 Research Groups in *General Engineering*. The Head of Group (name provided in parentheses in each section) provides overall direction, chairs group meetings and is responsible for mentoring new staff.

Advanced Composites Centre for Innovation and Science (Wisnom) – Composite materials offer excellent future growth opportunities due to their outstanding properties that can be tailored at the microstructural level. The Group leads the Faculty's **Advanced Materials** theme through research that spans the fundamental science of nanocomposites through to industrial impact on the challenges of manufacture and simulation of large composite structures [REF3b: *Structural Mechanics*].

Highlights: A multistable composite structure for morphing applications such as aerofoils was invented [Weaver-2, *Proc. Roy. Soc.*, 2012] and the shear modulus of graphene measured for the first time [Scarpa-2, *Nano Lett.*, 2009]. A novel, tow-steering approach for the defect-free manufacturing of complex composite parts is described in [Kim-1, *Comp. A*, 2012] and a unified method for understanding the initiation and propagation of fatigue damage in composites is presented in [Allegri-2, *Int. J. Fat.*, 2012].

Flagship projects in the Group's £17M portfolio include the EPSRC Programme Grant on *High Performance Ductile Composites Technology* with Imperial College, participation in the EPSRC *Centre for Innovative Manufacturing in Composites* led by Nottingham, and the Rolls-Royce University Technology Centre (UTC) in *Composites*. The Group's expertise and track-record underpinned the formation of the *National Composites Centre* (NCC) in 2011, and provides much of the core research programme. The NCC, hosted and owned by the University, provides an independent, open-access facility to deliver world-class innovation in the design and rapid manufacture of composites.

Future Directions: Multifunctional composites will be created combining enhanced structural performance with additional capabilities e.g. sensing, self-actuation, repair and morphing. The

origin and effect of defects will be understood further, and methods developed to avoid and detect them. Applied research will continue to focus on damage modelling (Rolls-Royce UTC), and manufacturing processes (NCC).

Applied Nonlinear Mathematics (Hogan) – Engineering requires predictive mathematical tools to deliver products and services. The Group works at the interface between mathematics and real-world applications, developing cutting-edge mathematical techniques that find application right across engineering but have particularly contributed to the Faculty's **Bio-Engineering & Health theme.**

Highlights: Flagship activities include the EPSRC Large Grant *Applied Nonlinear Mathematics: Making It Real*, and the *Centre for Complexity Sciences* CDT.

The first experimental confirmation of network models of opinion formation in multi-agent systems was shown [Gross-2, *Science*, 2011] and a unified approach to understanding sound emission from the inner ear was developed [Szalai-2, *Phil. Trans. Roy. Soc*, 2011]. The Group has contributed world-leading insights to the study of the collective behaviour of animals and humans, including a mathematical understanding of communities of nested species [Simini-2, *Nature*, 2013], the first identification of a stigmergic interaction beyond the realm of social insects (the avoidance of places visited by others) [Giuggioli-3, *Proc. Nat. Acad. Sci.*, 2011] and a mathematical model of human mobility and transportation networks [Simini-1, *Nature*, 2012].

The first large-scale analysis of ship movements yielded significant insights into world trade [Gastner-1, *J. Roy. Soc. Interface*, 2010]. A new classification of sliding bifurcations in piecewise smooth systems revealed 4 new bifurcations, one of which was subsequently seen in experiments [Jeffrey-2, *SIAM Review*, 2009]. The first proof of convergence of an adaptive strategy for controlling collective behaviour of networks is presented in [di Bernardo-1, *Automatica*, 2009].

Future Directions: the Group will put complexity science on a firm statistical basis by developing complexity models that describe the real world; it will seek to control multilevel complex networks, such as Smart Grids, via structure evolution, using coarse-graining and model reduction methods. Networks of piecewise smooth systems, which find application in topics such as earthquake engineering damage limitation, will become an increasing focus.

Communication Systems & Networks (Nix) – The Faculty's **Communications & Digital Media** theme reflects the importance of communications in our internet-connected lives and this Group is recognised worldwide for its contribution to the field. The Group's research is broad, covering the science of antennas and electromagnetics to the design and optimisation of communications networks. The Group benefits from outstanding industrial collaborations, many of which underpin the training and mentoring in the *Future Communications: People, Power & Performance* CDT.

Highlights: A city-scale deterministic radio wave propagation model was developed based on novel radar cross section theory. This unique tool was used to predict interference between broadcast towers and low-frequency airborne radars [Hilton-4, *IEEE Trans. Broadcasting*, 2013]. The work led to collaboration with Dstl on urban propagation and with Nokia Systems Networks on 3D channel models described in [REF3b: *Antennas*].

WiFi standards enable computers, tablets, mobile phones and set-top boxes to connect wirelessly to the internet. By combining electromagnetic theory with in-house bit-level simulations the Group developed a rigorous and repeatable WiFi test and verification process, leading to the research with Broadcom and BSKYB/Virgin Media described in [REF3b: *Wireless LAN*].

The Group has a major research project with Jaguar Land Rover to develop cellular infotainment systems, it also recently completed a project with a train operator to design the world's fastest WiFi connection to trains. In healthcare, it is well-known for innovative research in RF imaging for breast cancer [Craddock-1, *IEEE Trans. Antennas & Propag.*, 2009] [Klemm-1, *IEEE Trans. Antennas & Propag*., 2009] exploiting antenna and modelling skills described in [REF3b: *Antennas*].

Future Directions: The Group will build upon its track record in the areas of rapid communication-system prototyping, rigorous cross-layer optimisation for wireless connectivity, software-definable networks, mm-wave communications for gigabit cellular and in-home connectivity and intelligent-transport opportunities (wireless connectivity within and between vehicles). In partnership with Bristol City Council the Group will develop a city-wide experimental communications network as part of the £11.3M *Gigabit Bristol* project. The Group will continue to grow its healthcare activities,

building on body-area sensor networks in *SPHERE* and MRI coil design with Harvard.

Dynamics and Control (Neild) – Requirements for engineering structures increasingly emphasise efficiency and performance, resulting in ever-lighter and more-compliant structures with complex, nonlinear, dynamic behaviours to be understood and controlled. Through fundamental analysis and numerical simulation the Group leads the Faculty's ***Dynamics*** theme and provides tools to optimise structures and the experimental techniques to test them.

Highlights: The Group performed the first experimental continuation successfully carried out through saddle node bifurcation [Neild-2, *Phys. Rev. Lett.*, 2008] and the first application of pedestrian gait models to the problem of human-structure interaction [Macdonald-1, *Proc. Roy. Soc. A*, 2009]. The Group invented a novel continuous-scanning laser-vibrometry technique for dynamic testing [Di Maio-2, *Mech. Sys. Sig. Proc.*, 2010] and a new 5 degree-of-freedom gimbal method for aerodynamic testing [Lowenberg-2, *J. Aircraft*, 2013]. High profile awards include a Programme Grant on *Engineering Nonlinearity* and the AgustaWestland *University Technology Centre in Vibrations*. Impact includes 8 CASE awards with Airbus leading to their "dynamical systems toolbox" [UoA 10, REF3b] and KTP/TSB awards resulting in [REF3b: *Helitune*].

Future Directions: The Group will continue to focus on the dynamics and control of nonlinear systems. Particular emphasis, underpinned by recent recruitment (Jiang), will be on the development of: robust modal testing and identification procedures for structures with nonlinear characteristics; semi-active control methods, particularly those based on inerter systems; robust networked control systems that accommodate nonlinear effects and delays.

Earthquake and Geotechnical Engineering (Taylor) – This Group's focus is also within the ***Dynamics*** theme, in this case managing whole-system performance of civil-engineering infrastructure subject to environmental actions. With activities in earthquake engineering, non-linear dynamics, structure-foundation-soil interaction and geomechanics, a particular emphasis is placed on innovative experimental techniques integrated with non-linear modelling.

Highlights: The Group operates the 6 degree-of-freedom, 15 tonne EPSRC Earthquake Simulator (the leading European shaking table). It has led seven EU research teams through the FP7 *SERIES* project, involving 42 external researchers, in the experimental and theoretical investigation of a range of structural and geotechnical earthquake engineering problems, most notably on piled foundations [Taylor-4, *Europ. J. Mech. A/Solids*, 2013], [Mylonakis-1, *Earthquake Eng. Struct. Dynamics*, 2013]. The Group has developed a solution to the longstanding problem of obtaining displacements from seismic accelerometer data [Alexander-1, *Bull. Seis. Soc. Am.*, 2013] and spatial correlation models of ground motions during earthquakes have revealed features of particular interest for seismic risk assessment [Goda-3, *Bull. Seis. Soc. Am.*, 2008]. On behalf of EDF Energy, a £2M ¼-scale shaking-table model of an Advanced Gas-cooled Reactor (AGR) core is currently being built for the evaluation of plant safety.

A methodology to mitigate the urban landslide risk in developing countries [Holcombe-1, *Nat. Haz.*, 2012] led to impact described in [REF3b: *MoSSaiC*] and research on fibre reinforcement techniques for enhancing soil strength included new modelling approaches [Diambra-2, *Int. J. Num. & Anal. Methods Geomech.*, 2012].

Future Directions: The Group's approach, linking scientific advancements to whole-systems behaviour and applications, is deliberately positioned to address UK and global needs to extend and improve national infrastructure. Through its involvement in the £3.4M EPSRC *International Centre for Infrastructure Futures* project the Group will extend its whole-systems perspective to the development of new methods for explicitly integrating infrastructure business models with engineering models. This will augment continuing interests in nuclear safety, structure-foundation-soil-interaction in the seismic, offshore energy and transport theatres, and innovative structural and geotechnical system solutions including advanced composites. The Group will continue to lead the University's growing activities in the future cities and infrastructure domain.

Electrical Energy Management (Mellor) – The generation, distribution and use of electrical energy is central to the Faculty's priority theme in ***Energy & Sustainability***. Power electronics, electrical drives, electrical generation and power electronic converters have a vital role to play, not only in reducing energy demand, but also for renewable-energy conversion, low-carbon transport systems and resilient energy-supply networks.

Highlights: The Group has a research portfolio exceeding £6M, including 10 EPSRC grants. It has developed particular strengths in compact, highly efficient aerospace drives [Mellor-1, *IET Electric Power Applications*, 2011], vehicle electrical systems [REF3b: *Electric Drives*], in micro-renewable power management [Stark-2, *Applied Energy*, 2013] and energy harvesting technologies [Burrow-4, *IEEE Trans. Circuits & Sys.*, 2012].

The Group pioneered the profiled driving of silicon carbide devices to reduce electromagnetic interference and has on-going work to quieten high-speed gallium nitride (GaN) devices. The Group has exploited superjunction MOSFETS in 300V power conversion, where novel circuit topologies achieved 99% efficiency in a 1kW inverter.

The Group has strong industrial links, with 70% of its research being in collaboration with more than 20 UK and international companies; for example Goodrich Power Systems fund a UTC in *Aerospace Electrical Drives* and the Group partners with AgustaWestland in EC JTI *Clean Sky* projects. These links are highly beneficial in identifying industrial priorities and are often used to define the exemplars that demonstrate the group's research.

Future Directions: A new emphasis will be on component technologies and circuit topologies that exploit the high-temperature and fast-switching capabilities offered by emerging wide-bandgap power semiconductors; a collaborative centre with Physics on GaN devices has recently been established. Academic collaborations will be enhanced through the Group's involvement in the management of the EPSRC *Virtual Centre for Power Electronics* and the Group's leadership of the £2M work package on energy harvesting within the medical-sensing project *SPHERE*.

Fluid and Aerodynamics (Allen) – The Group is a key part of the Faculty's ***Dynamics*** theme, undertaking fundamental numerical, computational and experimental research to both accelerate aerodynamic design tools and produce more efficient designs for structures that interact with fluids, motivated primarily by applications in the aerospace and renewable energy sectors.

Highlights: The Group has developed a generic volume and mesh control method for Computational Fluid Dynamics (CFD) codes that in 3 years has developed from pure research to industrial use by [*text removed for publication*] [REF3b: *CFD*]. The first-ever freeform optimisation of a rotor blade was performed by the Group [Allen-3, *Opt. & Eng.,* 2013] and it has demonstrated new formulations for CFD simulations in moving-body problems [Rendall-2, *Int. J. Num. Methods in Fluids*, 2012].

The Group is the co-ordinator of the FP7 *FFAST* project which develops, implements and assesses simulation technologies to accelerate future aircraft design, and is involved in a number of EU projects relating to the *Green Regional Aircraft* initiative, including being coordinator of *CLAReT* and *MAWS*, and a partner in *ETRIOLLA*, *ESICAPIA* and *GLAMOUR* (total value of €10M). The Group is a partner in the FP7 *NOVEMOR* project on the development of novel morphing devices and is coordinator of the Marie Curie Initial Training Network on *Aircraft Loads Prediction using Advanced Simulation* (*ALPES*). It was awarded TSB funding via three projects under the UK Aerodynamics Centre call in 2012. The Group also obtained funding through the DTI/Industry joint-funded CFMS core programme [REF3b: *CFD*] and receives significant industrial funding from companies such as Airbus, Cobham Mission Equipment, MBDA and SSE Renewables.

Future Directions: The major goal for the Group is to achieve real-time simulation of the unsteady Navier-Stokes equations ("flying the equations") via four-dimensional space-time formulations. Exploitation of new computational technology, for example Graphic Processing Units, will be vital to achieve this goal, and the Group will pioneer generic code-porting solutions to future-proof simulation tools together with universal empowering technology to increase functionality of existing CFD codes. Fluid-dynamics research will be enhanced by the creation of the £500k Hele-Shaw lab, supported by new appointments in 2013 (Lawrie, Patterson).

Photonics (Rarity) – Photonics underpins a wide range of technologies but, as the backbone of the internet, it plays an especially central role within the **Communications & Digital Media** theme. This Group spans activities from near-to-implementation photonic systems and high-performance networks through to nanophotonics, advanced optical materials and devices, quantum information and fundamental photonic science. The Group has the facilities to fabricate and test optical devices and future communications networks. Joint appointments with Physics, close links to the Centre for Quantum Photonics and to the Centre for Nanoscience and Quantum Information are

enabling interdisciplinary projects across Physics, Biology and Chemistry.

Highlights: Contributions range from the first on-chip quantum photonic experiments [Cryan-4, *Science*, 2008], a novel laser source emitting Laguerre-Gaussian light featured on the cover of *Science* [Yu-1, *Science*, 2012] and the first realisation of on-chip correlated quantum walks [Thompson-2, *Science*, 2010] featured on the front page of the *Financial Times*. Thompson's Fellowship with Toshiba Japan led to the development of the new area of silicon photonics.

Research in wavelength-scale quantum optics has resulted in the development of a novel "spin photon interface" [Rarity-2, *Phys. Rev. B*, 2008] and fibre quantum sources [Rarity-3, *Phys. Rev. A*, 2009] leading to the award of an ERC advanced grant. This has been extended by writing and coordinating EU grants in the quantum networks area totalling a further £2.5M.

The addition of the High Performance Networks (HPN) activity (Simeonidou and 22 other staff) in 2012 broadened the Group into future multi–terabit photonic networks and led to 8 new grants (including a unique EU-Japan collaboration) in this area. The Group is at the forefront of a revolution in Software Defined Networking (SDN) research for Optical Networks.

Future Directions: The Group will continue to develop novel nanophotonic devices for switching and storage using both dielectric and metallic (plasmonic) approaches. The Group's facilities for fabricating and characterising optical materials will be enhanced through a new clean room and a new 3D photolithography machine "Nanoscribe". Real-world applications of photonic quantum information will be targeted through novel devices, circuits and proof-of-principle demonstrators. HPN research with the ***Communication Systems & Networks*** group will develop fully flexible networks carrying terabit streams seamlessly between optical and wireless components.

Robotics (Mayol-Cuevas*, submitted in UoA 11)* – Autonomous and cooperating machines, able to perceive and modify their environment, are a true milestone in engineering; this newly-formed but rapidly-growing Group has a focus in the **Dynamics** theme but addresses significant challenges across the topics of actuation and control, materials, verification, and machine vision.

Highlights: The Group has undertaken theoretical work, for example on the stability of discretized non-linear control systems [Herrmann-3, *Automatica*, 2008], while also achieving world-first demonstrations such as the first electrically-activated flexible skins with colour-changing properties [Conn-1, *Bioinspiration & Biomimetics*, 2012] and the first replication of asymmetric flexion in natural cilia in algae using smart materials [Rossiter-4, *J. Roy. Soc. Interface*, 2013].

The Group works closely with the Bristol Robotics Lab (BRL), a flagship partnership with the University of the West of England that includes one of the largest robotic testing facilities in the UK; the indoor flying arena at BRL hosts industrially-funded research into UAVs from DSTL, BAE and SEAS-DTC. The Group won funding from the ASTRAEA programme to develop autonomous air-to-air refuelling with Cobham Mission Equipment. Samsung Electronics has invested $400k in acquiring the Group's mapping algorithms for a major humanoid-robot project. Related visual-mapping work with UK's Blue Bear Systems, supported by the TSB, is enabling smart UAVs to map and navigate around buildings for industrial inspection [UoA 11, REF3b: *SLAM*].

Future Directions: The Group will develop a coherent integration of perception, action and intelligence to drive autonomous and cooperating machines. It will research actuation for soft bodies able to operate in environments unsuitable for rigid-bodied structures (e.g. inside biological tissue). The Group will develop distributed and compliant control strategies for safe human-robot interaction and set the agenda in the new area of formal verification of robotic systems.

Solid Mechanics (Truman) – Failure of engineering components and structures as a result of fracture and fatigue is not an unusual event, even today. The Group's research into materials, solid mechanics and engineering design underpins the metrology and integrity assessments that ensure efficient and safe operation of modern engineering structures and plant.

Highlights: The Group was the first to successfully measure residual stress in regions of high plasticity using mechanical strain-relaxation methods [Smith-3, *Int. J. Mech. Sci.*, 2011] and developed improved integrity assessments in the presence of residual stress and/or high temperatures [Truman-1, *Proc. Roy. Soc. A*, 2010]. Results from this research led to a spin-out [REF3b: *Veqter*] and are incorporated into *R6*, the leading international structural-integrity-assessment procedure. A systematic study of friction in machine elements [Booker-3, *J. Phys. D: Appl. Phys.*, 2008] has guided significant improvements in the design of aerospace bearings. The

Group manages the EDF *High Temperature Centre* through the provision of a rolling grant that feeds back into the UK nuclear safety-assessment code.

Future Directions: The Group will continue its activity in the areas of residual stress, fracture, fatigue and high-temperature materials behaviour. A step change in the understanding of high-temperature material behaviour (creep deformation and creep damage) will be achieved by systematically relating service history to underlying material response.

The Group will be at the centre of a growing nuclear activity which already includes the Bristol-Oxford Nuclear Research Centre but with plans for significant further investment to take advantage of academic expertise and geographical proximity to new reactor construction at Hinkley Point. It will research the influence of radioactivity on residual stresses in welded steel components, including the development of validation measurements and residual-stress measurement capability for radioactive components. New and advanced joining technologies for reactor systems will be pioneered by optimising fabrication parameters, microstructures and mechanical properties.

***Systems (Cliff**, submitted in UoA 11)* – It is a fact that engineered "hard" systems are embedded within "soft" human systems that include social, economic, regulatory and political drivers. The Group is developing a stakeholder-needs defined research programme rooted in the application of systems thinking across all the Faculty's research themes and across all sectors.

Highlights: The dynamics of crowd behaviour and disease propagation have been modelled [Johansson-1, *Phil. Trans. Royal Soc.*, 2009] [Johansson-2, *Lancet Infectious Diseases*, 2012]. Thermoeconomic analysis has been applied to decentralised energy systems for Indian villages [Tierney-1, *Energy*, 2012]. The Group collaborates with other universities and around 40 companies to make research contributions and technology transfers in various engineering fields, including the training of doctoral students in the *Systems* Industrial Doctoral Centre, and the Group's impact in industry includes [REF3b: *ULTra PRT*, *Nuclear Safety*].

Future Directions: The "systems architecting" concept will be developed further to achieve a better understanding of stakeholder needs, environmental factors and interoperability of systems during goal-setting and problem-definition stages. The Group's research in Safety Critical Systems will be consolidated by developing techniques for cross-disciplinary "wicked problems" with parameters including technical-risk analysis, uncertainty, due diligence, asset condition monitoring, security, sustainability and cyber-capability. It will produce analytical and empirical tools for the analysis of ultra-large-scale socio-technical software-intensive systems.

Ultrasonics and Non-Destructive Testing (Drinkwater) – Ultrasonic Non-Destructive Testing (NDT) is essential for the safe and efficient operation of high-value and safety-critical plant and for the adoption and subsequent monitoring of new **Advanced Materials**. The Group performs research into acoustics, elastodynamics, simulation, analytical modelling and signal processing for NDT, ultrasonic particle manipulation in biomedicine and tactile feedback.

Highlights: The Group is recognised for its work on ultrasonic arrays, with the more mature work now being exploited industrially as described in [REF3b: *Arrays*]. The Group was the first to demonstrate characterisation and sizing of sub-wavelength defects using ultrasonic array data [Wilcox-3, *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.,* 2008], a technique now supported by a unique elastodynamic finite-element technique that captures the radiation-to-infinity condition without absorbing regions [Velichko-2, *J. Acoust. Soc. Am.*, 2010]. The Group has developed a rigorous statistical framework for guided-wave structural health monitoring [Croxford-2, *Proc. Roy. Soc. A*, 2011] and was the first to trap micro-particles in phase-controlled ultrasonic Bessel beams [Drinkwater-1, *Proc. Roy. Soc. A*, 2012]. The Group led the £3.8M EPSRC-funded *Sonotweezers* interdisciplinary research programme.

The Group is a founder member of the EPSRC *Research Centre in Non-Destructive Evaluation (NDE)*, led by Imperial College, linking six leading university groups and 17 industrial users including Rolls-Royce, Airbus, BAE Systems, Shell, BP, GKN, DSTL, RWE and Eon. It also holds the *NDE* Industrial Doctorate Centre; together these are a powerful route to industrial impact.

Future Directions: The Group will consolidate its status as a leading NDT group and build on its developing biomedical activity. The major areas to be addressed include: self-optimising array processing tools for automated defect detection, classification and sizing without operator intervention; robust multi-wave measurement methods for detecting damage precursors in

industrial plant; fully-embedded guided-wave structural health monitoring sensors on composite structures; producing the world's first fully-dextrous ultrasonic particle-manipulation devices for tissue engineering and composite meta-material manufacture.

Water and Environment (Wagener) – Maintaining water security in a world stressed by climate change and increasing population is one of the fundamental challenges for humanity and central to the Faculty's vision in **Energy & Sustainability**. The Group develops new environmental models, as well as better uncertainty analysis and monitoring methods to characterise and simulate the environment through research in the core disciplines of hydrology, hydrogeology, hydroinformatics, hydrometeorology, water and health, and water quality.

Highlights: Contributions include the first study to show that rainfall event characteristics strongly control the value of streamflow observations to guide network design [Wagener-4, *Geophys. Res. Lett.*, 2008]. The Group showed how land-use changes for UK food production have exerted key controls on water quality since the 1800s [Howden-1, *Water Resources Res.*, 2011], and developed the first framework that can characterize all sources of space-time variability in flood events [Woods-2, *J. Hydrology*, 2010]. It also has a key role in establishing a global network of novel cosmic-ray sensors measuring soil moisture at unprecedented spatial scales [Rosolem-2, *Hydrol. Earth Syst. Sci.*, 2012], and has developed new algorithms for information retrieval from environmental sensors [Rico-Ramirez-2, *J. Hydrometeorology*, 2011].

Diverse funding sources include the EU FP7 and Marie Curie programs, EPSRC, NERC and the Leverhulme Trust. The Group currently leads a NERC project aimed at homogenising how risk and uncertainty are assessed across natural hazards (*CREDIBLE*). It recently concluded the *Aquatest* project funded by the Bill & Melinda Gates Foundation for water-testing in developing countries. The industrial impact of the Group's research is shown by [REF3b: *Ice Pigging*].

Future Directions: The Group will provide international scientific leadership in the search for new understanding of how and why the water environment is changing, for better simulation models with more realistic estimates of predictive uncertainty for effective adaptation and management, and for new approaches to monitor the environment.

c. People, including:

i. Staffing strategy and staff development

The University's decision to grow the Faculty of Engineering over the quinquennium has been strategic and driven by the national skills shortage in engineering at all levels, the strong demand from top-quality students to enter its programmes and the Faculty's sustained track record of research excellence. In pursuit of that strategy over the REF period, academic staff numbers in the Faculty have grown from 152 to 170 FTE.

Strategic Areas of Research Growth

Several research priorities were proposed in the 2008 RAE and additional priorities have also emerged since then; they have been nurtured via staff appointments and direct capital investments. The following lists some of these strategic appointments over the period within the five thematic areas:

i **Advanced Materials** – The award of the *Advanced Composites* Doctoral Training Centre led to five new appointments (Ciambella, Ivanov, Pirrera, Rahatekar, Trask) in the ***Advanced Composites Centre for Innovation and Science*** and enabled development of new research streams in nano-composites and polymer-composites. Links with the NCC have been strengthened by the recent appointment of Partridge as Chair to lead the *Composites Manufacture* Industrial Doctorate Centre as well as an imminent, related Chair position, jointly funded by NCC and Bristol. High-performance materials require new characterisation and testing capabilities and this aspect has been strengthened by a further three appointments (R. Smith, Velichko, Azarpeyvand in ***Ultrasonics and Non-Destructive Testing***, Peel in ***Solid Mechanics***).

ii **Energy & Sustainability** – The area of water quality and security is seen as a particular priority for growth, as evidenced by three appointments (Howden, Woods, Rosolem) in the ***Water and Environment*** group. Wagener was appointed in 2012 from Penn State University as Chair and Head of Group. Capability in the important area of efficient power electronics and

energy harvesting was strengthened with three lecturer appointments (McNeill, Yuan in ***Electrical Energy Management***, Barton in ***Applied Nonlinear Mathematics***). Further professorial appointments in ***Systems*** bring consideration of sustainability issues into the field of engineering design processes (Hicks, McMahon).

iii **Communications & Digital Media** – Two new proleptic appointments (Oulton, Thompson) were made in the ***Photonics*** group, reinforcing a vibrant research area for which the University now enjoys a worldwide reputation by adding complementary skills in solid-state optoelectronics and silicon-waveguide technologies. The optical devices and architectures area was strengthened by two further appointments (Nejabati, Zervas). Simeonidou was recently appointed as Chair and brought with her a 20-strong team specialising in high-performance networks.

iv **Dynamics** – Recent academic appointments in the ***Dynamics and Control*** group have strengthened rotorcraft dynamics (Titurus), nonlinear dynamics (di Maio) and vibration suppression (Jiang). Inman from Virginia Institute of Technology (Michigan since 2011) was appointed part-time as the Brunel Chair bringing internationally-renowned expertise in smart structures including energy harvesting. In the ***Fluid and Aerodynamics*** group, Cooper was appointed to the Sir George White Chair, co-funded by Airbus, to strengthen aeroelasticity and was subsequently awarded a RAEng Chair position. Three further appointments (Theunissen, Lawrie, Patterson) to that Group enhance experimental capability linked to simulation. Appointments with the University of the West of England are currently being made to enhance collaboration at the Bristol Robotics Laboratory.

v **Bioengineering & Health** – Six new appointments (Simini, Marucci, Giuggioli, Gross in ***Applied Nonlinear Mathematics***, Johansson in ***Systems***, Klemm in ***Communication Systems & Networks***) were made over the period with a further two being advertised (Toshiba-sponsored Chair and Lecturer in Biomedical Engineering). The Faculty was instrumental in bringing about the new cross-faculty *Elizabeth Blackwell Institute for Health Research* (www.bristol.ac.uk/blackwell).

Career Development

For academic staff, the overarching recruitment strategy in the Faculty of Engineering is to appoint those who have potential to achieve excellence in research. Heads of Research Groups and Heads of Departments are therefore involved with the Faculty Research Director, Head of School and Dean in staff appointments.

The Faculty, on occasion, recruits via the University's "Exceptional Talent" route whereby world-class researchers are headhunted because there is a strategic value to their appointment. For example R. Smith brings extensive industrial experience of aerospace inspection that links ***Ultrasonics and Non-Destructive Testing*** with the ***Advanced Composites Centre for Innovation and Science***; Simeonidou links the device-oriented ***Photonics*** group with the systems-oriented ***Communication Systems & Networks*** and ***Microelectronics*** groups; Wilson's expertise in traffic modelling brings together ***Applied Nonlinear Mathematics*** and ***Systems***; McMahon and Partridge are linking composites research into manufacturing.

Another recruitment route is by a "proleptic" appointment to an academic post upon completing a research fellowship; these are offered to outstanding Research Fellows (e.g. Oulton, Thompson).

The University is committed to the *Concordat to Support the Career Development of Researchers* from initial recruitment through early-career mentoring to continuing professional development. The University, through its Research and Enterprise and Development team, run staff development workshops covering, for example, grant-writing, leading research teams and public engagement.

Early-career academics are given a light lecturing load (usually no more than one course in their first year). They have priority for PhD studentships and for funding to pump-prime new activities, attend conferences and develop industrial links. For example, Yuan's £3.6k pump-priming award for a *Fault Tolerant Wind Power Converter* resulted in an *IEEE* paper [Yuan-1, *IEEE Trans. Sustain. Energy*, 2012] and a *Building Global Engagement in Research* award to visit Blaabjerg (Editor-In-Chief of *IEEE Trans. Power Electronics*) at Aalborg University to collaborate on large wind turbines.

Staff are encouraged to apply for Fellowships and assisted to do so by mentoring, mock panel interviews and presentation training by outside experts. As detailed in section (e), 27

competitively-awarded Fellowships were awarded or held during the REF period.

Wherever possible, the career development of Research Fellows is encouraged by including them in proposals as research co-investigators and they also may co-supervise PhD students. They are encouraged to engage in the academic community, for example Wrobel is co-editor of *IEEE Transactions in Industry Applications*.

Diversity

The Faculty supports a diverse body of staff and students through the implementation of current University equality policy and through its own practices. *General Engineering* has a truly international demographic: of the ~70 academic staff appointed over the REF period ~30 have international backgrounds including ~10 from countries outside the EU such as Canada, USA, Japan, Russia, India, Algeria, Brazil, New Zealand and China. Similarly, of the ~190 post-doctoral research staff appointments over the REF period ~100 have international backgrounds including ~55 from outside the EU. Examples of diversity in recent academic staff appointments include:

- International backgrounds (e.g. Wagener from USA, Gastner & Gross from Germany, Inman from USA, Goda from Japan, Marcos from Spain).
- Leading female researchers (e.g. Simeonidou and Partridge via the exceptional talent route).
- Leading researchers from industry (e.g. R. Smith from Qinetiq, Yearworth from Hewlett-Packard).

Whilst it is acknowledged that there are low numbers of female engineers in the sector, the University of Bristol was a founder member of the Royal Society Athena SWAN (Scientific Women's Academic Network) Charter and one of the first universities to be awarded the Athena SWAN Bronze Award for excellence in science, engineering and technology employment in higher education, with particular regard to gender equality. The Faculty is working towards independent recognition under the SWAN Charter and strongly supports the recruitment and development of future female academic leaders; in 2012 it appointed two female professors via the exceptional talent route. There is always at least one female academic on promotions panels and the focus is on the quality of research rather than quantity, helping to ensure that any periods of maternity leave or flexible working patterns are properly considered.

ii. Research students

The Faculty recognises the far-reaching benefits of training postgraduates within cohorts and its expansion in this type of postgraduate provision has resulted in it hosting a total of five prestigious Doctoral Training Centres (DTCs), Centres for Doctoral Training (CDTs) and Industrial Doctorate Centres (IDCs), representing a current EPSRC investment of £27.1M:

- *Complexity Sciences* DTC (cohort 10 p.a., £9M, 2006-17).
- *Advanced Composites Centre for Innovation & Science* DTC (cohort 12 p.a., £7.1M, 2009-13).
- *Future Communications: People, Power & Performance* CDT (cohort 10 p.a., £2.2M, 2011-9).
- *Systems* IDC (cohort 10 p.a., £5M, 2009-18).
- *Composites Manufacture* IDC (cohort 10 p.a., £3.8M, 2012-5).

The Faculty's postgraduate-training provision has been further strengthened by the announcement in November 2013 of a further six CDTs to be led by Bristol (including *Quantum Engineering*, *Future Autonomous and Robotic Systems* and *Water Informatics: Science and Engineering*).

Bristol is also a partner university in schemes led by other institutions including the UK Research Centre in *Non-Destructive Evaluation* IDC (2011-8, ~two EngDs p.a. at Bristol, £2.2M from EPSRC) and the *Large Scale Complex IT Systems* IDC (2008-16, ~two PhDs p.a. at Bristol, £4M from EPSRC). Marie Curie Initial Training Network (ITN) participation includes the €1.4M ITN on *Aircraft Loads Prediction using Advanced Simulation* and the *SHEMat* (*Self HEaling Materials*) ITN (two students, 2013-15, €276k at Bristol).

All postgraduates benefit from working within one of the 13 Research Groups; participating in their weekly internal seminars (disseminating research findings but also developing presentation skills), meeting industrialists and joining reading groups in particular topics. They are encouraged, where appropriate, to attend specialised MSc taught courses offered at Bristol. Progress is monitored through an annual review, during which the supervisors provide written feedback and at which the students themselves are invited to reflect on progress.

The Faculty's future postgraduate strategy will be further enhanced by the creation of the *Bristol Doctoral College*; this new £650k venture will underpin the development of doctoral education across the University, providing a clear and visible focus (both externally and internally) for postgraduate training. It will support a high-quality student experience, to build on best practice and encourage skills training.

d. Income, infrastructure and facilities

Income

As described by the introduction in section (a) and in REF4, *General Engineering* has performed strongly over the REF period in financial terms; the continued and growing strength of its grant portfolio reflecting not only the reputation and quality of its research, but also its success in building collaborations around significant engineering challenges with partners in academia and industry. The Faculty's Industrial Liaison Office assists to create links with industry. This ranges from mentoring undergraduate students through to fostering research relationships, for example, via the Faculty's annual Research Reception, which in 2013 hosted more than 140 visitors from industry.

Within *General Engineering* the flagship research grants include:

- *Quantum Optics in Wavelength Scale Structures* (Rarity, ERC Advanced Grant, €2.5M, 2010-5).
- *Engineering Nonlinearity* (Wagg, EPSRC Programme Grant, £4.2M, 2012-7).
- *Sonotweezers* on ultrasonic manipulation (Drinkwater, EPSRC Large Grant, £3.8M, 2009-13).
- *HiPerDuCT (High Performance Ductile Composite Technology)* (Wisnom, EPSRC Programme Grant, £6.4M, 2011-7).
- *Aquatest* project developing a microbial test of drinking water for field use in developing countries (Gundry, Bill & Melinda Gates Foundation, £8M, 2008-12).
- *CREDIBLE* on natural hazard uncertainty (Wagener, NERC Programme Grant, £2M, 2012-7).
- *Underpinning Power Electronics* (Mellor, EPSRC Programme Grant, £2M, 2013-7).
- *SPHERE* a data-fusion approach to e-health (Craddock, EPSRC IRC, £12M, 2013-8).

Another source of external research income is through the provision of consultancy and other professional services. Such activities are a means of forming deep industrial links and actively developing impact outside academic circles. Notable examples over the REF period include:

- Use of shaking table for seismic assessments for EDF and others (Taylor, Crewe).
- Peer review of the National Nuclear Laboratory's ultrasonic inspection protocol for safety-critical evaporator tubes (Drinkwater, Velichko).
- Landslide risk-management advice to the World Bank Latin America and Caribbean Region, Disaster Risk Management Group (Holcombe, Anderson).
- Modelling flight refuelling hoses and drogues for Cobham Mission Equipment (Rendall, Allen).
- Extensive work on bridge and cable dynamics for a variety of national and international clients including Clifton Suspension Bridge Trust, Mott MacDonald, Femern A/S (Macdonald).
- Advice to QinetiQ on ultrasonic inspection of submarine tiles (R. Smith).

Infrastructure and Facilities

The Faculty has state-of-the art research laboratories which, building on the £25M *BLADE* investment in 2004, are underpinned by a rolling programme of investment. Over the REF period there has been a total of £13.1M infrastructure investment in the Faculty together with a further investment totalling £60M in the National Composites Centre. Much of the former has been targeted at the Faculty's five strategic themes, for example:

i **Advanced Materials** – £5.4M for new laboratory and office space for ***Advanced Composites Centre for Innovation and Science***, plus £3.1M awarded in 2013 by EPSRC for equipment for the laboratory, extending its already world-class composites fabrication and testing facilities.

ii **Energy & Sustainability** – £1.4M, comprising a £250k refurbishment of the ***Electrical Energy Management*** group laboratories, direct industry investment (Emerson Control Techniques, Qinetiq) of around £300k in new equipment and a £750k refurbishment of the 310 m^2 hydraulics laboratory used by the ***Water and Environment*** and ***Fluids & Aerodynamics*** groups.

iii **Communications & Digital Media** – £2.5M, including a £1M refurbishment of 200 m^2 of

laboratory space complete with state-of-the-art suite of network test equipment for traffic up to 1 Terabit per second per channel, the "Nanoscribe" 3D photolithography machine and a further investment of £1.2M for a new clean room, expected in 2014.

iv **Dynamics** – £750k comprising a £250k refurbishment of laboratories used by ***Dynamics and Control*** and ***Earthquake and Geotechnical Engineering*** groups and £500k for fluid dynamics.

v **Bioengineering and Health** – £60k refurbishment of office space and facilities.

Further to these Faculty investments, relevant large University infrastructure investments include:

- High Performance Computing Centre (£12M investment since 2008) provides 202 TFlops of computational power and is heavily used by many of the Faculty's Research Groups (its executive committee is chaired by Allen from the ***Fluid and Aerodynamics*** group).
- Nano-Science and Quantum Information Centre (an £11M facility with vibration and acoustic noise levels among the lowest in the world) provides advanced experimental and material-characterisation facilities and is used by the ***Ultrasonics and Non-Destructive Testing***, ***Advanced Composites Centre for Innovation and Science*** and ***Photonics*** groups.
- Bristol Robotics Laboratory (BRL), a £1.6M facility operated jointly with the University of the West of England, provides 3000 m^2 of laboratory space, including 26 research bays, six laboratories, two indoor flying arenas with motion capture infrastructure and teaching facilities. BRL is heavily-used by the ***Robotics*** and ***Dynamics and Control*** groups.

e. Collaboration or contribution to the discipline or research base

The University recognises the international nature of top-flight research and actively promotes overseas collaborations. These include institution-level initiatives such as:

- *Worldwide Universities Network Researcher Mobility* programme (14 outward secondments for staff and students in the Faculty funded over the REF period).
- EPSRC *Building Global Engagements in Research* (£150k of institutional funding went to academics in this Unit of Assessment over the period).
- Strategic bilateral partnerships with major universities including Kyoto, Auckland, Sydney, UC San Diego, Zhejiang, Michigan, Los Alamos Labs, Washington and Penn State universities. For example, the 2013 Bristol-Kyoto symposium involved a visit of over 90 delegates from Kyoto working with more than 150 Bristol staff in 13 parallel workshops.

Examples of major international research projects in *General Engineering* include:

- Thompson awarded €2.2M in FP7 for research in quantum photonics.
- The Intergovernmental Technical Cooperation Program (TTCP) project on Notched Composites involves the ***Advanced Composites Centre for Innovation and Science***, the University of British Columbia and the US Air Force Research Laboratories.
- The EU FP7 *FFAST* projects (€4M) and *NOVEMOR* (€1.9M), Marie Curie Initial Training Network *ALPES* (€1.4M) and various EU *Clean Sky* projects relating to the *Green Regional Aircraft* initiative (€10M), led by or involving the ***Fluid and Aerodynamics*** group.
- The multi-partner EC JTI *Clean Sky* projects *ELETAD* and *HERRB* for which the ***Electrical Energy Management*** group is co-ordinator and technical lead (total of €3.2M).
- *LIGHTNESS* on low-latency and high-throughput dynamic network infrastructures for high-performance datacentres, led by Simeonidou (€2.5M).
- *SERIES* on seismic-engineering testing, led by Taylor (€2.5M).
- *BRITESPACE* on semiconductor laser sources for space applications (€2M).
- *CONTENT* developing a next-generation ubiquitous converged network infrastructure to support the network of the future, led by Simeonidou (€2.8M).
- *QWAD* on the topic of quantum waveguides, led by Rarity (€1.7M).

Much international collaboration takes place between individuals. Over the REF period, staff have hosted numerous visiting international academics and industrial figures, such as: Todd (University of California San Diego) leading to [Croxford-2] and a recent successful EPSRC proposal; Chang (University of Central Florida, sponsored by Royal Academy of Engineering); Bringi and Thurai (Colorado State, funded by Leverhulme); Archfield (US Geological Survey); O'Brien (NASA); Advani (Delaware); Jiao (Beijing University of Technology); Gandhi (Pennsylvania State);

Krauskopf (University of Auckland); Futatsugi (NEC, Japan); Meaney (Dartmouth College, USA); Kudo (NTT, Japan); Genter and Gvozdenovic (Vienna).

Collaboration with Research Users

The Faculty has an exceptionally strong track record of collaboration with industry, leading not only to funding of research projects but also strong mutual interactions on the development of research strategy. Some of the most significant and strategic collaborations over the period include:

- D. Smith, Royal Academy of Engineering Professor supported by EDF-Energy and Rolls-Royce, researching fracture of materials and locked-in stresses in engineering components.
- Cooper, Royal Academy of Engineering Airbus Sir George White Chair in Aerospace Engineering, an expert in Flight Physics who also advises Airbus on their research direction.
- The ***Earthquake and Geotechnical Engineering*** group is developing a 1/4 scale physical model of an aged graphite core of a nuclear reactor for EDF Energy to be fitted with ~15,000 monitoring instruments to characterise its non-linear dynamics (£2M, 2012-5).
- The ***Ultrasonics and Non-Destructive Testing*** group is a founding partner of the UK *Research Centre in Non-Destructive Evaluation* (2003-date) with 15 industrial partners each contributing funds alongside EPSRC to give an annual budget of ~£1M – this has provided a natural route for rapid industrial exploitation as evidenced by [REF3b: *Arrays*].
- The AgustaWestland UTC in *Vibration and Structural Dynamics* in the ***Dynamics and Control*** group (£2.6M, 2007-13).
- Safran (Goodrich) Power Systems UTC in *Aircraft Electrical Drive Systems and Technologies* now in its 14th year has accrued £1.7M of research funding direct from the industry sponsor and affiliated TSB projects. The UTC has provided a foundation for a rapid growth in aerospace electrical machines and power electronics research.
- The Rolls-Royce UTC in *Composites* in the ***Advanced Composites Centre for Innovation and Science*** group (£4.5M, 2007-15).
- The ***Communication Systems & Networks*** group has a strong relationship with Toshiba. McGeehan and subsequently Craddock have been employed two days a week as Managing Director of Toshiba's Telecommunications Research Laboratory. This laboratory, wholly owned and operated by Toshiba, has funded many projects and PhDs in the UK, notably over £2M at Bristol, as well as a Chair in Biomedical Engineering which is currently being filled.
- Vestas preferred partnership with the ***Advanced Composites Centre for Innovation and Science*** (£1.4M).

Interdisciplinary Research

The University recognises the value of interdisciplinarity at the highest level and has created a small number of cross-faculty research institutes specifically to enable breakthroughs at the boundaries between established subjects:

- The **Elizabeth Blackwell Institute for Health Research** fosters collaborations between engineers, scientists, industry, clinical practitioners and patients through fellowships, targeted workshops and pump-priming. The Faculty participates fully in the Institute and, in addition to playing an important role in the successful *SPHERE* IRC proposal, the Institute has funded activities including Warr's 6 month Fellowship on Magnetic Resonance Imaging at Harvard.
- The **Cabot Institute** studies risks and uncertainty related to climate change, natural hazards, food and energy security, governance and human impact on the environment. Its vision is to fuse rigorous statistical and numerical modelling with a deep understanding of interconnected social, environmental and engineered systems. The Institute brought together a consortium of natural hazard researchers through its *BRISK* initiative who wrote the successful £2M *CREDIBLE* NERC Programme Grant bid led by the ***Water and Environment*** group.

Many individuals and groups are involved in interdisciplinary research. Some of this activity is supported through major collaborative research grants including:

- *SPHERE* (Craddock) – this £12M EPSRC grant is led by the University of Bristol, together with Southampton and Reading, partnered by Bristol City Council, IBM and Toshiba. *SPHERE* will advance the state of the art in health monitoring through collaboration between clinicians (from Cardiovascular Disease to Orthopaedics), clinical scientists (from Experimental Psychology to

Nutrition) and researchers in communications, machine vision and energy harvesting.

- *Sonotweezers* (Drinkwater) – this £3.8M EPSRC project researched electronically-controlled ultrasound tweezers for use in forensic science or homeland security, for applications such as cell-sorting and counting of micro- and potentially nano-materials. The interdisciplinary project brought together fluid mechanics at Bristol, transducers and system implementation at Dundee, particle manipulation at Southampton and assay application at Glasgow.
- *Aquatest* (Gundry) – in remote areas of the developing world a lack of skilled personnel makes the provision of drinking water testing regimes unrealistic. To address this problem the Bill and Melinda Gates Foundation funded this £8M project, led by Bristol along with the Health Protection Agency, the World Health Organisation, Oxfam, the Universities of California Berkeley, Cape Town, North Carolina, Southampton and Surrey.

In addition, the University and Faculty both actively promote new interdisciplinary research opportunities through various "pump-priming" funding mechanisms:

- Burrow's £7k pump-priming grant in 2009 for field studies of remote monitoring of glacial fields led to two NERC grants worth a total of £820k.
- Rahetakar's pump-priming grant *Engineering of Nanocomposites for Aerospace & Biomedical Applications* created an interdisciplinary collaboration with Centre for Organized Matter Chemistry and the School of Cellular and Molecular Medicine resulting in two journal papers (*Biomacromolecules* and *Composites Science and Technology*). A second pump-priming award on cellulose-based actuators led to collaboration with the Bristol Heart Institute.

Academic Leadership

Fellowships and Prizes

General Engineering includes among its staff: one Fellow of the Royal Society (Ewins), two Fellows of the Royal Academy of Engineering (Ewins, McGeehan), three Fellows of the Institute of Mathematics and its Applications (Champneys, di Bernardo, Hogan), two Fellows of the Royal Aeronautical Society (Cooper, Lieven), a Fellow of the IEEE (di Bernardo) and three Fellows of the Institute of Physics (Rarity, Rorison, Truman).

Royal Academy of Engineering Research Chairs were awarded to Cooper, D. Smith and O'Brien (a joint Physics-Engineering appointment, submitted in UoA 9) and, over the REF period, staff in *General Engineering* held the following competitive Fellowships: EPSRC Advanced Research Fellowships (Allen, Bond, Macdonald, Truman, Wagg, Wilcox, Wilson), EPSRC Career Acceleration Fellowships (Jeffrey, Klemm, Oulton), EPSRC Early Career Fellowships (Neild, Thompson), EPSRC Manufacturing Fellowship (R. Smith), Marie Curie Fellowships (Gastner, Marshall, Westerberg), Humboldt Research Fellowships (Goda, Gross, Wagener), ERC Advanced Investigator and Early Career Fellowships (Rarity, O'Brien), a Royal Society Industrial Fellowship (Mellor), three Royal Academy of Engineering Fellowships (Azerpeyvand, Payton, Peruzzo), a NASA Science Fellowship (Rosolem) and the Toshiba/EPSRC Fellowship (Thompson).

The quality of the Faculty's research has been recognised through more than 50 prizes and other honours, including Royal Society Wolfson Merit Awards (Rarity, O'Brien, Wisnom), best-paper prizes in topics as diverse as Mechanical Engineering (Potter) and Environmental Modelling (Wagener), the IET Emerging Technologies Prize (Yu, O'Brien, Rarity), a national prize for Engineering (Richardson) and several IET awards (e.g. Thompson). O'Brien received the 2010 Adolph Lomb Medal of the Optical Society of America, the 2010 Moseley medal and prize of the Institute of Physics. Achievements outside academia include the Toshiba International Award for the most outstanding executive (McGeehan).

National Advisory Roles and Policy-Making

Engineers at Bristol play an important role nationally, influencing policy on a host of matters ranging from the provision of the optical networks that underpin all research in the UK (Simeonidou: Member of the JANET UK Optical Steering Group), through to contributing to the UK's technology roadmap in key areas (e.g. Wilson, member of the *Aerospace Power Systems National Technical Committee*; Weaver, member of the *Materials and Structures National Technical Committee*). The experience of senior Faculty members is sought for key functions in the region (e.g. McGeehan, Board Member of the West of England Local Enterprise Partnership).

Research Council and EU Strategy

Over the REF period, members of the Faculty (Beach, Hicks, Hogan, Drinkwater) have served on four separate EPSRC Strategic Advisory Boards, taking the lead in drawing up EPSRC's future research agenda. Simeonidou is a member of the European Commission delegate group for international collaborations with Brazil, Japan and Korea and the advisory group for Horizon 2020.

Services to Professional Bodies

Staff in *General Engineering* contribute to the life of many relevant professional bodies: senior staff chair technical committees, education panels, and local chapters for the Institute of Structural Engineers (Crewe), the Society for Industrial and Applied Mathematics (Champneys), the American Society of Civil Engineers (Weaver), the Institution of Mechanical Engineers (Booker), the American Institute of Aeronautics and Astronautics (Lowenberg), the Institute of Physics (Oulton), the IEEE (di Bernardo, Herrmann) and the International Association for Hydrological Sciences (Woods).

Consultancies, Directorships and other Services to Industry

Engineering is the application of the sciences to solve real world problems; it is therefore natural and desirable that the expertise of the Faculty's staff is extensively sought by Industry. During the REF period, seven Directorships in Industry have been held by Faculty staff (Craddock, Hicks, McGeehan, Nix, Potter). These notably included substantial commitments over the period by both Craddock and McGeehan as Executive Directors of Toshiba group companies.

Many staff undertake consultancies with organisations ranging from the World Bank (Holcombe on landslide risk), the Clifton Suspension Bridge Trust (Macdonald advising on structural risks to this engineering icon), Cisco (Simeonidou as Technical Advisor), NASA (Weaver, space launch vehicles) to Apple (Nix, advising during an IP dispute with Nokia).

Conference Chairs

More than 27 international conferences have been chaired or organised, notably including the *17th International Conference on Composite Materials* (Wisnom), the *AIAA Atmospheric Flight Mechanics* conference (Lowenberg), the IET's premier conference (Mellor, academic chair of *IET Power Electronics, Machines and Drives*), the largest European optical communications event (Simeonidou as TPC Chair for *ECOC*), the UK's largest antennas and propagation conference (Craddock, co-chair of *LAPC* 2011) and numerous others.

Invited Lectures, Plenary and Keynote Speakers

More than 30 invited lectures, plenaries and keynotes have been given during the period (e.g. Hogan: *International Congress in Industrial and Applied Mathematics* in Vancouver; Nix: *Consumer Electronics Show*; Weaver: *International Conference on Composite Structures*, Wisnom: *ICCM* conference in Montreal; Wilcox: *Quantitative NDE* conference in Denver).

Editorships

Many staff have senior editorial roles for major journals. Since 2008 these have included Wisnom as Editor-in-Chief of *Composites Part A and B*, Champneys as Editor of the *IMA Journal of Applied Maths*, Inman as Editor-in-Chief of the *Journal of Intelligent Materials Systems and Structures* and di Bernardo as Deputy Editor-in-Chief of *IEEE Trans. on Circuits and Systems*.

Outreach

As can be seen from the breadth of the case studies in REF3b, the UK and society in general benefit in many ways from the contribution that Engineers make. Staff recognise their responsibility to inspire a new generation of future research leaders; this includes working with local schools (Crewe, Drury), the E3 Academy and the Electronics Skills Foundation (Beach). Staff helped organise the *Bristol Festival of Ideas* (Oulton), and participated in the Royal Society Summer Exhibition (Weaver, Wilson) and the Cheltenham Science Festival (Drinkwater). Television work includes separate appearances by Craddock, Johansson and Nix on BBC's *Bang Goes the Theory* and film-making with Oscar-winning Aardman Animation (Craddock).