Institution: University of Sussex

Unit of Assessment: 12 – Engineering

1. Unit context and structure, research and impact strategy

Engineering and Design is a substantial, expanding unit of 26.2 FTEs, comprising seven major research groups, and is housed within the School of Engineering and Informatics, one of ten Sussex Schools of Study. We are committed to delivering inclusive, sustainable research and innovation that enriches lives both locally and globally. Our overriding strategic objective since 2014 has been to use horizon-scanning to expand our research portfolio, income and outputs, whilst building on existing excellence and recruiting new high-calibre, foresighted researchers and partners to facilitate greater vitality. This strategy has significantly developed the productivity, collaborative endeavours, and commercial and social impact of existing groups; and it has led to the creation of new research clusters in Communications, Robotics and Space Science.

Our research groupings have been formulated to span the UKRI themes of Digital Economy, Energy, Engineering, Global Uncertainties, Healthcare Technologies, Information and Communication Technologies, Living with Environmental change, Artificial Intelligence, Space Science, Physics and Materials Science, and Manufacturing the Future. Via this research portfolio, we are also addressing the Global Challenges theme of "Sustainable Economies and Societies", which is greatly facilitated by the diversity of our staff and postgraduates. Each research group contributes to several of these multidisciplinary themes. There is significant collaboration between research groups and academics and organisations across the globe (Figures 1-3), which enables a flexible strategic response to UK government and international research initiatives via appropriate configurations of knowledge sets; hence we deliver on research priorities that benefit the changing requirements of the UK's economy and society.

Integration and communication between research groups occurs formally via School-level termly research and knowledge exchange meetings and informally via ad hoc meetings and research seminars. The department is distinguished by its formidable inter- and cross-disciplinary approach, with a strong commitment to general engineering, both in-house and through close collaborations with leading researchers locally and globally in diverse fields from podoconiosis diagnostics in Ethiopia to reduction in gas-turbine CO_2 emissions for GE Aviation, USA.

Our expansion strategy has resulted in significant successes: research applications have increased considerably, from £3.9 million in 2013 to £38.2 million in 2019; for the same period research income increased from £608k to £1.643 million per annum; peer reviewed publications rose from 74 in 2013 to 111 in 2018. We are also committed to making our work accessible: since 2013, 59.7% of our publications are open-access via the gold (25%) and green channels, available on Sussex Research Online, our institutional repository. Numerous reference machine-learning datasets for human activity recognition have been made open-access (see: (v) STRC) and we regularly provide free technical advice to companies, NHS and government bodies.

In the 2020 Times Higher Education world rankings for Engineering (1098 entrants), we were ranked 32nd for citations and 17th equal for international outlook, and 151-175 in the world overall. This placed us =17th in the UK for Engineering and Technology, narrowly second in the UK for citations with a score of 98.2, and 3rd in the UK for international outlook.

The Department's seven significant research groups are:

(i) The Centre for Advanced Communications, Mobile Technology and IoT (ACMI), led by Nekovee, conducts research in advanced communications, 5G/6G mobile technologies influencing international standards, the Internet of Things (IoT) and free-space optics. Professor Nekovee sits (as the only UK academic) on the EU's 5G Infrastructure Association, where he advises the European Commission on 5G and beyond-5G Strategic Research Agendas. The

ACMI Group works closely with Samsung, Vodafone, Huawei, BT, NXP, Cobham Wireless as well as being actively involved in important UK, European and international standardization and regulatory bodies.

(ii) The Dynamics, Control and Vehicle Research Group (DCVRG), led by Dunne, undertakes sustainable automotive research and fundamental work in: dynamics, control, connected and autonomous vehicles, hybrid electric/electric vehicles, combustion emissions. Professor Dunne and his group have collaborated continuously with Jaguar Land-Rover, Ford, Toyota, and Ricardo for more than two decades. Supported by these companies, successful funded research projects are making significant contributions in reducing CO_2 and other damaging emissions.

(iii) The Industrial Informatics and Signal Processing Research Group (IISPRG), led by Chatwin, focusses on signal processing techniques ranging from security applications, to medical diagnostics of images, to bioimpedance spectroscopy for disease classification in Ethiopia. Their algorithms and software have had global impact and are being used in 23 countries spanning Europe, North America, Asia and Australasia. Feedback plc and IQ-AI Ltd sell the group's TexRAD software for oncology and urolithiasis assessments worldwide (see Chatwin impact case study (ICS)), having embodied it in hardware – an electrical impedance tomography (EIT) system – for non-invasive 3D imaging of breast cancer tumours.

(iv) The Robotics and Mechatronic Systems Research Group (RMSRG), led by Glovnea, conducts research into systems that are designed to perform autonomous tasks in diverse environments. Highlights include: a 3D-printed triggerable drug delivery system using magnetic fields that has recently received media attention. Robotics research concentrates on physical human-robot interaction (pHRI) and its applications in industrial robots and rehabilitation, including pioneering work that makes use of game theory for pHRI in teleoperation (an article in *Nature Machine Intelligence* was reported by more than 16 news outlets).

(v) The Sensor Technology Research Centre (STRC), led by Roggen, undertakes research into wearable technologies exploiting machine learning for computational behaviour analytics and the fundamentals and applications of electric field sensing in medicine and safety devices for tired vehicle drivers. The emphasis is on novel sensing modalities, embedding intelligence into miniature and mobile devices, using multimodal sensor fusion approaches that scale into sensor-rich environments, and lifelong adaptive paradigms. This group developed an electric potential sensor that has been commercialised (see Prance ICS).

(vi) The Space Research Group (SRG), led by Barnett, is active in wide-bandgap semiconductor detector physics for space science and associated harsh environment instrumentation. They are world leaders in radioisotope micro-battery research and have created revolutionary spacecraft attitude determination systems. The applications of the group's work are in the development of new extreme environment tolerant semiconductor devices and instrumentation for X-ray astronomy and space science, as well as spin-off applications in scientific, commercial, defence and homeland security. In 2016 Anna Barnett won the prestigious Philip Leverhulme Prize, which recognises outstanding research achievement.

(vii) The Thermo-Fluid Mechanics Research Centre (TFMRC), led by Long, undertakes aerodynamic, heat transfer and structural dynamics research in the area of gas-turbine technology with GE aviation and MTU Aero Engines. This research has had global impact through delivering CO_2 emission reductions in aircraft engines via experimental assessment of internal air systems (see Long ICS). They also use their modelling and design expertise to support many different industrial sectors: from baking muffins to water treatment and combating COVID-19.

Priorities such as global impact and research reach, *inter alia,* are advanced via a termly School Research meeting, chaired by the School Director of Research & Knowledge Exchange (DRKE), and attended by the Head of School (HOS), Head of Department (HOD) and all research group

leaders from UoAs 12 and 11, which ensures coherence with individual and group research plans. Global research strategy is developed in this forum, potential impacts are identified and, where appropriate, funding (provided by the University) is allocated to support their development. The research groups are tasked with identifying research with impact: in the current round we had nine possible ICSs, arising across all seven research groups. This was reduced to the required three via an EDI-compliant review process organised by the University-level Research Quality and Impact team. There is an active management strategy to generate further 4* ICSs for the next 5-year period and there are already plans for spin-out companies from current research in the different groups. Four embryonic ICSs have already been identified and will be supported and developed for the next REF.

Future research strategy is generated and expedited by the HOS, HOD, DRKE and the School Research Committee, and both informs and responds to the rolling 5-year research plans formulated by individual faculty. The unit's general policy is to track UKRI, EU and Government initiatives to ensure that the department, via its external collaborators, is able to respond to research calls in a timely manner. We intend to continue developing the strategy formulated in 2014, which has brought research and external funding expansion. In addition, new strategic strands have been created to enhance flexibility and formally encourage the rich cross-disciplinary collaborations that have developed in this REF period. These new strands are focused on the incorporation of three integrating themes *(Txx): Health-TH, Artificial Intelligence-TAI, Sustainable Energy-TSE*. These themes are led by **Rendon-Morales, Birch, and Sorguven** respectively, each of whom is active in promoting cross-group collaboration to create projects and funding bids within these themes.

The introduction of *TH, TAI* and *TSE* has already strengthened our research groups' opportunities, and is encouraging the formation of spin-out companies to exploit outputs such as nuclear batteries, medical diagnostics, and security technologies. Each is associated with a dedicated, well-founded specialist laboratory, with the necessary equipment and technical support to produce world-class outputs, and in the coming years they will further increase the quality and reach of our research. In addition to these future-oriented cross-disciplinary initiatives, our future research strategy is closely bound into Sussex's recently-created Future Technologies Laboratory, opened by the then Minister of State for Universities and Science, Jo Johnson, in 2017. With state-of-the-art facilities for work in robotics and autonomous systems exploiting AI, the FTL is the result of an £11million governmental and university investment in the innovative engineering required to address future global challenges – challenges our research (and research across Sussex) is committed to addressing.

2. People

Staffing strategy, staff and research student development, equality and diversity

Our staffing strategy prioritises appointments that support our research and teaching strategy, in order to build on and complement existing strengths, maintain critical mass in each area and across the enabling technologies and, where appropriate, to enhance or develop new collaborations. For example, as part of our expansion by 3.4 FTEs since 2013, the department supported DCVRG by appointing Peter Fussey as an industrial research professor: at 40% FTE, he spends 60% of his time as the Head of the Powertrain Controls Department at Ricardo Ltd. This approach ensures that new appointments are aligned with our impact strategy, which in turn is supported by the available physical infrastructure.

Posts are advertised and appointed in line with University procedures, within which equality and diversity is fully integrated (as it is in all University procedures, including promotion and staff development). In addition, Sussex is a member of the Athena SWAN charter for the advancement and promotion of the careers of women in STEM subjects, and has a supportive policy on flexible working. Engineering is one of the most ethnically diverse departments in the University, boasting staff of fifteen different nationalities spanning the globe. Our success in managing diversity is underpinned by the University's Equality, Diversity and Inclusion (EDI)

policy, which is strategically committed to reducing the gender pay gap, securing a race equality charter, joining the top 100 employers in the Stonewall UK Workplace Equality Index, and to becoming a disability confident leader. This is supported by staff networks, Dignity and Respect Champions, benchmarking and training programmes, and our unit-specific EDI Champion (currently Rendon-Morales). Our gender distribution is: 11.1%-female, 88.9%-male; Disability: zero stated; Ethnicity: 40.7%-BME, 51.9%-non-BME; FT/PT: 88.8%-FT, 11.1%-PT; age-range: 30-50=59.3%, over 50=40.7%. The selection of research outputs used self-assessment and internal review followed by external assessors in an EDI-compliant process that was monitored by our EDI Champion. The diversity of our staff means that we have outstanding links to global research (Figures 1-3) and the global economy *(placed 3rd in the UK for international outlook (THES)).*

All new permanent staff are provided with research equipment set-up funds and funding for their first PhD studentship. They are also given a reduced teaching load and no substantive administrative roles. Those taking up their first academic position have a probationary period, the goals and targets for which are agreed between the probationer and the line manager, with progress reviewed at regular intervals. On completion of probation, the progress reviews are replaced by standard annual appraisals, which are used to help to assess progress against previous objectives and aspirations; these enable the revision of goals and targets to reflect an individual's position on their career trajectory, with the aim of achieving and maintaining research of significant international influence. All staff must develop their own 5-year personal research plan, which is updated annually. These individual plans are then integrated into the relevant research group's 5-year plan; this process is an important factor in establishing research group cohesion and guiding future recruitment. All staff have an annual appraisal, which refers to the individual's personal research plan; this is used by managers to guide each researcher's career path and promotion, whilst ensuring their integration with their research group and its impact strategy.

Early-career researchers have a senior member of staff as a mentor, and are supported and guided by colleagues within their research group. All staff must also submit potential external grant applications for rigorous internal review. This review and feedback process ensures that less-experienced staff develop grant-writing skills under the guidance of senior colleagues. Junior staff are encouraged to apply for the EPSRC first-grant scheme, and there has been notable success in winning these grants. Formal Staff Development is provided by the University's Staff Development Unit through a comprehensive programme of courses and activities for enhancing research and professional skills, which are fully compliant with The Concordat to Support the Development of Researchers. The University's Research and Enterprise Division also runs regular training on research-related topics, often led by external specialists. Sabbatical leave is used to support early career development: for example, Barnett was supported in this way and subsequently won the Philip Leverhulme Prize, was promoted to Professor, and Deputy PVC for Research. Barnett has also managed to attract significant amounts of research funding.

As careers develop, targeted support from experienced senior colleagues is used to help individuals attain the next level, as defined by promotion procedures. At the most senior levels, staff continue to be supported by special training opportunities provided by the University. Staff development at all levels is greatly enhanced by a strongly supportive and collaborative culture within the research groups, which enables the exchange of ideas and best practice. This culture allows privileged access to research resources and an extensive national and international network of senior colleagues – a network that saw 63 scholars, including senior professors and government advisors, visiting from across the globe during the REF period – all of whom enrich the research environment and partake in lasting collaborations.

A framework of ethical and legal standards is provided by the University and professional societies to which staff belong. There is a School Research Ethics Officer who deals with low-risk undergraduate and postgraduate taught research. For research proposals, there is the University-level Science & Technology Cross-Schools Research Ethics Committee (SCI-TEC C-

REC), which runs on a continuous cycle of ethical review throughout the calendar year. Academics are members of a number of different professional societies, which also provide ethical guidance and advice on professional standards of behaviour; these include the IMechE, ASME, RAeS, IET, IEEE, IOP, ACM, BCS, SPIE, OSA. These societies also provide a forum for exchange of ideas and collaboration opportunities with industry and academic colleagues via a series of colloquiums and international conferences.

During this REF period, six faculty members left to take up promoted positions at other institutions and there were two retirements. We have subsequently rejuvenated their research groups by making eighteen new academic appointments, three of which were at Professorial level. Five faculty members were promoted to Professor, three promoted to Reader, and five promoted to Senior Lecturer. In terms of Research Assistants/Fellows, there were sixteen leavers and eighteen new starters.

Research students

The unit supports a thriving community of research students who follow the doctoral programme. Its aims are:

1) to provide students with the full breadth and depth of knowledge and skills required to be independent researchers;
2) to prepare students for careers in academia or the commercial and public sectors.

Applications to study with the unit come as a result of academics' reputations, and nationally- and internationally-advertised research projects and studentships. During this REF period, 49 research scholarships were awarded, which comprise: 7 EPSRC, 4 industrial, 3 Chinese Scholarships Council, 3 Chancellors International Research Scholarships, and 30 School Scholarships, which are deployed to support grants and the research of new members of staff.

At University level, all doctoral students are supported by the Doctoral School and are required to participate in transferable and professional skills training, tailored to individual need. They also have the option to participate in a range of other academic and professional training opportunities. The Student Life Centre provides coordinated access to a full range of special-study, personal and financial support services. Within the unit, doctoral students are supported by a Director of Doctoral Studies and associated administrative team. The unit runs a two-term research-training module for all first-year students, focused on skills at a level designed specifically to bridge those provided at University level and specific training provided within research groups – the primary communities for research students. The specific training related to students' research draws upon the ongoing research activity of their group and is supported by research fellows and experienced fellow students within the group.

To ensure research students experience a flavour of research undertaken beyond engineering, a weekly joint seminar series is held with members of this unit and those comprising UoA 11 (Computer Science and Informatics), which visitors, staff and research students all attend. Every student is also given the opportunity to present at an international conference, and hence is required, in preparation, to present his or her research as part of the in-house seminar series.

The research degrees undertaken cover the spectrum of activities offered by and across groups, and other disciplines. Examples of work extending beyond the unit include a range of medical image-processing projects supervised jointly by IISPRG and the Schools of Life Sciences, Psychology and the Brighton and Sussex Medical School (BSMS). There are typically 60 PhD students associated with the groups at any one time, with each permanent member of staff supervising approximately three students. Students have at least one formal supervision meeting per month, which the student minutes; for audit purposes this meeting is recorded on the Sussex Direct database. All students have at least two supervisors with relevant expertise. In the first year of study, supervisors conduct a six-month interim appraisal and each year a

formal annual review is held, which includes a substantial report and *viva*-style interview. The submission rate within four years is greater than 70%.

3. Income, infrastructure and facilities

Table 1 below outlines the research income attributable to the unit during this REF period. It can be observed that the scale of applications and awards are on a rising curve with an average success rate of 10%, illustrating that our research strategy has been highly successful. Not included in the Table is a recent £11 million investment in the Future Technologies Lab. The sources of income are diverse, with the industrial element (UK and non-UK) demonstrating the significance and impact of the unit's work over a wide sectorial range.

Each individual's five-year research plan contributes to his or her group's and the unit's plans, which include anticipated funding and exploitation points. The entrepreneurial environment is evidenced by the formation of TexRAD Limited, Feedback plc and Stonechecker Software Ltd (see Chatwin ICS) and licence agreements with Plessey for the Electric Potential Sensor (EPS) generic measurement technology (see Prance ICS). The Space research group are world leaders in radioisotope micro-battery research. They have produced some of the world's highest internal conversion efficiency radioisotope micro-batteries: two patent applications have been filed and planning is underway for a spinout company. This rising level of income ensures sustainability and demonstrates the alignment of our research with national priorities.

Table 1 Funding applications and awards

Year	13-14	14-15	15-16	16-17	17-18	18-19	Total
Applications £000s	3,909	8,088	8,549	12,179	13,975	38,239	84,939
Awards £000s	130	1,175	973	2,663	2,523	1,284	8,748

Infrastructure and facilities use

A specialist technician is attached to each research group, and the unit has well-maintained mechanical and electronics workshops. Electron microscopes and mass spectrometers are accessed via the School of Life Sciences. Magnetic resonance imaging (MRI) and Computed tomography (CT) are accessed via collaborations with the Clinical Imaging Centre in BSMS and collaborations with NHS hospitals. The technical infrastructure is maintained through a combination of the relevant elements of external funding and University funds. Each group has essential software including: ANSYS; CAD (mechanical and electronic); MATLAB and toolboxes; Multisim; LabVIEW; and mobile and wireless development platforms.

In addition, each group has a local High-Performance computer cluster and access to the University's High-Performance computing facilities. The Space research group use the EPSRC National Epitaxy Facility at Sheffield to grow some of the materials used in their semiconductor devices.

ACMI
The Centre is well-resourced with a range of Communication and IoT Hardware and Software equipment, including OMNeT++ network simulation tools.
Major equipment includes: six Rhode and Schwartz RF test chambers; two National Instrument LTE SDR platforms; six Rhode and Schwartz 1 GHz spectrum analysers; 28 GHz, mechanically rotatable channel sounder; various other radio and free-space optical transmission and reception modules, including WiFi, ZigBee and LiFi.
Use of Facilities: **Nekovee** has close collaborations with Samsung (through a 5-year project on artificial intelligence for mobile networks), who have dedicated 0.15 FTE of a principal research engineer to provide consultancy, specialist knowledge and technology transfer to industry

standards for the duration of the project (with a value of £75k). Others include BT and Vodafone, through an ESRC-funded pilot on Connected and Smart Care – *(TH, TAI)*. **Ali** has 5G research collaborations for testbed demonstrators using close links with Huawei and Cobham. Cobham Wireless have provided several industrial scholarships to support two research students. **Sheng**'s research interests cover connected vehicles, IoT, and cloud/edge computing. His research is funded by EPSRC (EP/P025862/1), Royal Society (IE160920) and the University of Sussex. He is also in receipt of an emerging research award for eHealth *(TH)* from University of Sussex. Sheng works with NXP Semiconductors, who have donated microcontrollers for intelligent vehicle development and have also contributed equipment to an EPSRC-funded project awarded to Sheng. He also collaborates with Toyota USA who are providing in-kind support in the form of consultancy and specialist knowledge for automotive communication systems. **Oner**'s research is on blind estimation for decryption, cognitive radio, signal identification, spectrum sensing and statistical signal processing.

DCVRG has 4 specialist laboratory facilities:

The ***Engine-Focused Laboratory*** *(TSE)* – estimated equipment-replacement value £3m – contains four engine test facilities:

- a heavy-duty diesel test-cell, with transient dynamometer, currently being used for EU-funded research involving a 7.2L I6 Caterpillar engine;
- a gasoline test-cell, with steady-state dynamometer, currently being used for industry-funded research involving an I3 DISI engine;
- a steady-state multi-cylinder production engine test-bed with dynamometer, various uses;
- two single-cylinder engine test-beds – current use: i) a Ricardo Hydra test engine, and ii) a Ricardo E6 variable compression ratio test engine.

The laboratory also contains specialist instrumentation and diagnostics for IC engine research – PIV and PDA in-cylinder flow diagnostic tools – dSpace hardware, emissions measuring equipment, real-time cylinder pressure measurement, engine-block acceleration measurement and Holomodal (ESPI-Laser-based) structural noise, vibration and harshness measurement systems.
Use of Facilities: **Dunne** and his group have collaborated continuously with Jaguar Land-Rover (EPSRC: EP/E03246X/1), Ford, Toyota, and Ricardo for more than two decades. Supported by these companies, successful funded research projects are making significant contributions in reducing CO_2 and other emissions via evaporatively cooled IC-engines *(TSE)* (EPSRC: EP/M005755/1), (Ricardo), and a resonating free-piston generator (DSTL) *(TSE)*. Professor Dunne has been awarded 4 patents (European Patent App. No.10718646.2; European Patent App. No. 08845993.8; United States Patent No. US8519553B2; UK Patent No: GB2454360).

The facilities in Skarvelis-Kazakos's ***Energy and Transport Laboratory*** include a Real-Time Power System Simulator, as well as battery and solar inverters as power sources. A weather station supplies real-time wind, solar and other measurements. The lab is able to emulate a small power network (micro-grid) and researchers are able to implement and validate novel techniques on energy network reliability, resilience and renewable energy integration *(TAI, TSE)*.
Use of Facilities: Innovate UK funded electrical and thermal energy storage for the reduction of emissions; the Energy Systems Catapult and an EU Grant also supported research into reconfigurable DC distribution networks *(TSE)*.

The facilities in Moradinegade Dizqah's ***Smart Vehicles Control Laboratory*** include a dSPACE SCALEXIO hardware-in-the-loop simulator of Hybrid Electric/Electric Vehicles (HEV/EVs), a full suite of dSPACE ASM models for real-time simulation of vehicles, a UWB-based Indoor GPS system, a SIMULINK-based development kit of the Woodward's ECUs, CPU/GPU processing power for real-time processing, bespoke self-driving rovers and Quanser QCar modules, and a Mini-Roller road test-rig to evaluate the parameters of the rovers *(TAI, TSE)*.
Use of Facilities: Model-based optimal design and energy management of hybrid electric/electric vehicles and advanced control strategies for connected autonomous vehicles.

Liang's specialist ***Thermodynamics, Combustion, Heat Pump, Cryogenics and Refrigeration Laboratory*** is focussed on linear compressor technology.
Use of Facilities: Research interests are in low-carbon cooling and heating systems using novel technologies, and the particular application areas are cam-less combustion engines, linear machines and control, Stirling coolers and refrigeration, which is supported by the Asa Briggs Fellowship fund *(TAI, TSE)*.

IISPRG
Laboratories contain: three 2.4m-by-1.8m vibration-isolated optical tables; a custom-built x640 florescence microscope; a Photek CDIR detector photon-counting camera; several CMOS SPAD cameras; 2 Nvidia GPUs; 10 Xilinx FPGAs donated by Xilinx; a frequency-doubled Nd+3:YAG laser; Casix LDC1500; Picoquant PDL800D pulsed laser diode; Power Technology Inc Laser diode; several Uniphase He-Ne and diode lasers; Meadowlark liquid crystal spatial light modulator (SLM) for the production of dynamic computer-generated holograms, correlation filters and optical convolutional neural networks; a CCD-based beam visualisation system; micro-positioning translation stages; interferometers; optics; CCD and CMOS cameras; data acquisition and processing tools; Impedance analysers; a CNC-controlled Excimer laser microfabrication system; and five high performance GPU-workstations for the implementation of high-speed data processing and deep-learning algorithms.
Use of Facilities: Funded research includes: MOD target recognition and tracking; multi-camera tracking for 2020 Imaging Ltd. Current research, funded by 2020 Surveillance Ltd, is focussing on intelligent security systems, by using automatic tagging of people, locations and actions through deep learning *(TAI)*. **Birch** works with Acutance Scientific Ltd on advanced optical design and Gunnebo Ltd on access control technologies; the work with Gunnebo has led to an Innovate UK-KTP that will develop AI, computer vision and multi-sensor approaches to improve the security and safety of their gate system *(TAI)*. Electrical impedance tomography for non-invasive 3D imaging of breast cancer tumours was funded by a venture capital company WZVI and led to the successful implementation of a prototype breast cancer tomographic system (IEEE Trans on Medical Imaging) *(TH)*. BritMedical Ltd are funding a project to detect cancer in CT and MRI data using enhanced AI convolutional neural networks *(TH, TAI)*. **Chatwin** is part of the NIHR Global Health Research Unit for Neglected Tropical Diseases based in BSMS. This work uses bio-impedance spectroscopy for the detection of podoconiosis in Ethiopia, funded by NIHR (NIHR: 16/136/29) *(TH)*. **Young** recently gained a Leverhulme research grant that aims to more closely mimic the biological developmental processes under genetic control, to develop a method for evolving structures of engineering relevance. He has also secured a grant with BSMS from the Charity Versus Arthritis entitled: "Does peripheral neuroinflammation predict chronicity following whiplash," to which he is contributing advanced image-processing expertise to assess nerve damage *(TH)*.

RMSRG
Laboratories include:
Industrial automation: Flexible Manufacturing System with PLC, Pneumatics, Electro-pneumatics, Sensors, Actuators, Drives, Industrial robots, Industrial Networks, and Conveyor Belt, Machine-Vision, and computing equipment,
Autonomous vehicles: Drone Zone with Motion-Tracking System; autonomous ground robots; Zumo robots; VEX Robot kits.
Medical simulation facility: Incubator and 25 weeks premature baby ECG simulator (Respiration, Atrial, Ventricular and Junctional tachycardia, Atrioventricular Block, Hyperkalaemia, etc.(RAVTAH)). Pregnant mother and baby HR simulator (RAVTAH).
Light microscopy and metrology facility: Bright-field microscope, Florescence microscope, Selective-plane illumination microscope, Opto-mechanics, Lenses, filters, EOTLs, Light sources.
Machine facility: High-speed CMOS, sCMOS and CCD cameras; Machine-vision optics; Stereoscopic vision cameras; Plenoptic cameras.
Human-robot interaction laboratory / Robotics facility: 2 Mitsubishi RV-2AJ robots; 2 built-in-house robots; ATI Mini-40 force/torque sensor; H-MAN (a planar robotic platform suitable for

testing of algorithms for physical human/robot interaction enabled by its simple structured workspace and basic 2-DOF mechanics).
5G communications facility: 70 MHz to 6 GHz USRP Software Defined Radio Devices; 10 MHz to 6 GHz USRP Software Defined Radio Reconfigurable Devices; High gain passive antennas.
Tribology Laboratory / Optical interferometry test facility: PCS Instruments Optical interferometry test-rig of EHD film measurement (has the ability to measure film thickness of down to two nanometres and friction forces, in concentrated contacts with pressures up to 2GPa. The rig has an adaptor for studying of heterogeneous slip/non-slip bearings); Mini Traction Machine (MTM) (a general purpose test-rig for friction measurement in various conditions of load, temperature and kinematics. It can be adapted for the study of hard or soft contacts, wear measurements, as well as for electrical capacitance measurement); Solartron A1260 Impedance/gain-phase analyser.
These new facilities were created via a recent £11 million government investment in the newly-founded Future Technologies Laboratories.
Use of Facilities: **Glovnea** secured funding for dielectric spectroscopy studies of lubricants, particle modelling of fluid-flow and contact mechanics (SKF); **Rendon-Morales** for a medical device for monitoring foetus' electrocardiogram activity non-invasively, to inform clinicians on the status of the baby (EPSRC: RES/0560/7386/004) *(TH)*; **Nguyen** for the OPTIMIN "Optimising Energy Management in Industry" project with Brunel University, Queen's University Belfast, Cranfield University, Tata Steel UK, DPS-Global, Econotherm UK, Ltd., Crowley Energy Ltd., (EPSRC: EP/P004636/1) *(TSE)*; **Yanan Li** secured EPSRC New-Investigators Award, in collaboration with two industrial partners GripAble and Articares, and another award for Human/robot interaction *(TH, TAI)*.

STRC
The main laboratory contains: A surface-mount PCB fabrication facility; PCB milling machines (LPKF PROTOMAT S103) to allow the use of high pin-density IC's and ball-grid arrays; other items: surface polisher, high-temperature furnace, high-impedance component and dielectric characterisation equipment, and an impedance analyser; microwave and RF test and measurement equipment, spanning audio frequencies to 22 GHz; low-noise, low-frequency test and measurement equipment, including spectrum analysers and noise measurement apparatus.
Additional specialist laboratories include: A clean-room containing resist spinners, optical lithography and e-beam lithography, ion etching, thermal evaporation, sputtering, plasma etching and chemical/wet bench equipment; an Optomec Aerojet HD: a high-resolution 3D printer allowing printing on arbitrary surfaces.
Use of Facilities: **Roggen** uses machine-learning techniques and miniature sensors to recognise and understand human activities (e.g. EPSRC: EP/N007816/1) and context, such as attention management during surgery (EU) *(TH, TAI)*. His ongoing research embedding intelligence into miniature and mobile devices and multimodal sensor-fusion approaches has been funded by Google, Huawei, NUMERO EIGHT, Metropolitan Police, Unilever, EPSRC (e.g. EP/R013837/1). **Prance** created the electric potential sensor (EPS), which has been commercialised by Plessey Semiconductors in an on-chip version – the EPIC sensor (DSTL) – for medical (Facial Palsy), healthcare, forensic and consumer applications *(TH, TAI)*. The group is also working with: Philips Healthcare, on electrophysiological monitoring for home healthcare (EU); Meggitt Sensing Systems Ltd (IUK), on sensors for aerospace applications; and Rescon Ltd, a research and consultancy SME developing systems in the area of human performance; on the development of a face-mounted EPS data acquisition headset (EMTEQ Ltd. Precision Varionic International Ltd); and additionally, supported by GCHQ, on the development of a RF-NMR system using electric field detection. **Munzenrieder** secured funding for shape sensing textile for orthotics (EPSRC) and also medical wound management *(TH)*.

SRG
In addition to specific expertise in specialist areas of microelectronics, space, defence, and aerospace, SRG offers a wide variety of general high-performance engineering and physical science research, consultancy, and contract services. SRG provides its services from dedicated, access-controlled laboratories and offices to facilitate confidential research for

government and industry.
Space Research Group capabilities and facilities include: Electrostatic discharge-controlled laboratories and materials handling; Radioactive materials handling; Optical engineering dark-room; Electromagnetically shielded room and measurement; Specialist instrumentation design, fabrication, and characterisation; Radiation detector and spectrometer design, fabrication, and characterisation; Optical systems design, fabrication, and characterisation; Space mission development, planning, and analysis; Development of custom Monte-Carlo models and signal processing codes; Simulated-environment testing and qualification (-70°C to 180°C, 1 bar to 10^{-12} Bar); X-ray fluorescence spectroscopy; Radiation detection and measurement; UV, X-ray, γ-ray, and β^--particle illumination of samples and devices; Optical microscopy; Ultra-low-noise electronics development and analysis; Semiconductor characterisation, including ultra-low current and capacitance measurements.
Use of Facilities: Funded by STFC and EPSRC, **Barnett** has worked extensively with colleagues at the EPSRC National Epitaxy Facility to produce numerous III-V epitaxial wafers of exceptional quality by metalorganic vapour-phase epitaxy; those wafers and devices fabricated from III-V materials have enabled Barnett to secure her place as the world's leading expert in III-V radiation detector physics, her research is supported by several grants (including STFC: ST/M004635/1, ST/R001804/1; EPSRC: EP/P021271/1) and to establish the UK's foremost group working on radioisotope voltaic micro-batteries (STFC: ST/M002772/1, ST/P001815/1; UKRI). A new technique for spacecraft attitude determination has been invented and is being commercialised (STFC).

TFMRC
Occupies a dedicated building containing the following experimental rigs:

- a multiple cavity rig, to investigate flow and heat transfer in high-pressure compressor internal air systems (stacked titanium discs 220 mm radius, heated outer ~250°C, max 8000 rev/min);
- a rim-seal effectiveness rig, to investigate ingestion of hot mainstream gas into a turbine rotor-stator cavity (an engine-representative single-stage axial-turbine, rated 400 kW, pressure ratio ~2.7:1, driven by air from the DART compressor, maximum speed 14,000 rev/min);
- a bolt windage rig, to investigate flows around rotating bolts with optical access for PIV; measurements of torque are made on the drive shaft, driven up to 10,000 rev/min.

A range of high-pressure compressors drive the rigs: a modified Rolls-Royce DART aero engine-driven compressor (10 kg/s, 3.5 bar, believed unique); Atlas CopCo ZT250 (0.8 kg/s; 7 bar, gauge-cooled and dried to 25 ºC); or Atlas CopCo ZT110 (0.6 kg/s; 7.5 bar, gauge-cooled and dried to 25 ºC). Measurement and telemetry capabilities to capture and transmit data include: liquid-crystal techniques; Scanivalve DSA systems; Laser-Doppler Anemometry; Particle-Image Velocimetry; hot-wire anemometry. Datatel radio telemetry provides non-contact transmission of rotating thermocouple signals. In addition, the centre has significant experience in high density installation of temperature and pressure sensors in rotating rigs. Computation is undertaken using in-house structured staggered grid-based LES solver for both compressible and incompressible flows such as combustion, and a highly parallel unstructured compressible LES-solver for aero-acoustics and heat transfer. A wind-tunnel and 3D printing facilities also enable validations of simulations to be undertaken.
Use of Facilities: **Long** secured funding from GE for research into gas-turbine internal air systems, in particular, the thermofluid mechanics of rotor-rotor and rotor-stator cavities *(TSE).* **Kanjirakkad** is working with power generation companies GE and Siemens on flow leakage effects (tip/shroud/hub/seal), flow and heat transfer on blades and within rotating cavities as well as boundary-layer flow transition *(TSE)*. **Sorguven** collaborates with a number of companies completing an axial-fan design for Aironn and the design and simulation of a centrifugal water pumps for Alarko-Carrier *(TSE)*. Modelling of the muffin-baking process for Beko plc has delivered oven design optimisation via simulations to predict muffin colour and height. Simulation of the primary clarifier baffles for Southern Water have shown that a horizontal baffle increases the effectiveness of the sedimentation process. The UK-SPINE Knowledge Exchange Fund has

supported interdisciplinary research into the use of Electronic Delivery Devices for the efficient delivery of inhaled pharmaceuticals to lung tissue *(TH)*. **Petrov** is funded by MTU Aero Engines AG (MTU-G1804) to develop computer codes to perform rapid sensitivity analysis of their bladed-disk gas-turbine components, which will reduce greenhouse gas emissions *(TSE).*

4. Collaboration and contribution to the research base, economy and society

The unit has made a series of profoundly important contributions in research, economic, and societal terms. Our research strategy strongly supports interdisciplinary and collaborative research resulting in numerous collaborations across the University and with other national and international universities. We are collaborative by nature, and work with a myriad of national and extranational companies and charities.

An impactful example of such collaborations is the NIHR Global Health Research Unit for Neglected Tropical Diseases located in BSMS. IISPRG is a partner in this, and the research unit collaborates with three African partners (CDT-Africa at Addis Ababa University, Ethiopia; the Armauer Hansen Research Institute, Addis Ababa, Ethiopia; and the Mycetoma Research Centre, University of Khartoum, Sudan) plus: Lymphatec (USA), Global Health Technologies (USA), Imperial College, Helmholtz (Germany), London School of Hygiene and Tropical Medicine, and NePAN (Ethiopia) *(TH)*. The crucial importance of this work and its impact on the lives of many individuals has recently been recognised in the award of an OBE for services tackling neglected tropical diseases to the NIHR Unit's co-director, Professor Gail Davey.

Locally within Engineering there are a significant number of inter-group collaborations, PhD co-supervision, joint projects and publications that demonstrate the centrality of collaboration to our research. The development of impact case studies (ICSs) also strategically motivates and captures work that contributes to society and the economy: all seven research groups are working on new ICSs, with ambitions to spin-out new technology and companies. These activities receive active support from the School Research & Knowledge Exchange Committee, the University and the Sussex Innovation Centre.

Each of our research groupings has specific successes to highlight, as follows:

ACMI is very active in collaboration with industry, academia, funding bodies and policymakers around the mobile, wireless and IoT ecosystem. **Nekovee** is a member of European Telecommunications Standards Institute - Industry Specification Group on NFV and the IEEE Technical Committee on Cognitive Networks. He has been a keynote speaker at: the International Telecommunication Union (ITU) Summit on 5G (September 2019), 5G Global Summit (June 2019), the annual IET 5G event (2017/18/19); and a panel speaker at: the IEEE WCNC (April 2019) and IEEE PIMRC (September 2019), and the Global 5G technology Congress (Shanghai, 2017/18/19), the UK Spectrum Policy forum (May 2018) and Telco AI Summit (November 2019). Nekovee and Ali have ongoing collaborations with Plum consultancy – a specialist consultancy to communication regulators in the UK and externally – and this has resulted in extensive 5G radio propagation measurement campaigns at the Sussex campus (at 3.5 and 28 GHz), which have been published in IEEE and IET conferences as well as having formed the basis for new 5G signal propagation models by the ITU. **Ali** was a member of the technical program committee for several IEEE international conferences and was an invited Keynote speaker at the International Conference on Artificial Intelligence and Internet of Things, Paris 2018. He collaborates with Govia Thameslink railway, Cobham Wireless, and Plum consulting. He is associate editor of the journal *IET Wireless Sensor Systems* and on the editorial board of the *International Journal of Sensor Networks and Data Communications*. **Zheng** has collaborations with Beihang and Tsinghua Universities on connected self-driving cars, which is partially supported by a grant from the Royal Society. He collaborates with NXP Semiconductor UK, who provide him with equipment. Toyota USA are providing support on automotive communication systems. He was conference chair of: the 5th International Conference on Internet of Vehicles 2018; the IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015); and is on the organising committee for the IEEE International Conference

on Sensing, Communication and Networking. He is editor in chief of *IGI Global International Journal of Vehicular Telematics and Infotainment Systems*. He is also on the editorial board of: *IEEE Access and the Elsevier Ad hoc Networks Journal*. He is a member of IoT Standardization Research Groups at IEEE ComSoc Communities. **Oner** is an editor of the *IEEE Communication Letters.*

DCVRG research is key to the long-term activities of a number of commercial organisations, evidenced by collaborations of longer than a decade, including with: Jaguar Land Rover Engineering Centre (adaptive cylinder-pressure reconstruction for production engines); and Hadley Industries, UK (informing cold-rolled forming design and analysis). More recently, commercial collaborations of two or more years include those with Ford, Denso, and Ricardo (particularly on the EPSRC-funded project: Evaporative Cooling of Internal Combustion Engines, 2015-2019 (for which Ricardo funded completion) *(TSE)*. DCVRG has also received £400k from the DSTL-DASA in the past 2 years. Group faculty work with the Transport Knowledge KTN and a range of universities, including: Oxford University, Brunel, Beijing Information Science and Technology University, University of Birmingham, Coventry University, and Queen Mary University of London. The Group's industrial sponsors and partners include: the EPSRC, the EU, BP, the UK Government, Caterpillar, Jaguar Land Rover, Ford, Denso, Ricardo, Garret, Spirax Sarco, Oxford Magnet Technology, Allen-Bradley, Johnson Matthey, AVL, Flander's Make (Belgium), and Quanser, (Canada). Engagement activities include a keynote presentation **(Dunne**) at Linear Power, September 2015. Dunne is on the editorial board of the *Journal of Sound and Vibration*, *Journal Vehicles*, *Journal of Autonomous Intelligence*. **Fussey** is Chairman of the IMechE Automotive Division Southern Region. As a Member of the EU Automotive Research body EARPA and the Technical Committee for the Symposium for Combustion Control (2015 to present), he influences sustainable research policy at international level. **Skarvelis-Kasakos** is on the Smart Grid Technical Committee's Journal Activities Sub-Committee (proposing topics for special issues of the *IEEE Trans Industrial Electronics*). **William Wang** was awarded 'Excellent Oral Presentation Award' for the paper: 'Sliding Power in Aircraft Landing' at the 4th International Conference on Mechanical Design and Engineering, 28th-31st March 2018, Beijing. **Chang Wang** was invited to talk on '3D Printing and Total Hip Replacement' at the 11th International Congress on Orthopaedic Advanced Techniques and Clinical Translational Research, Shanghai *(TH)*. **Dizqah** has active collaborations with the Tier-1 supplier FEV in Germany and with four universities throughout Europe. **Kun Liang** is a programme committee member of ICEC (International Cryogenic Engineering Conference) 2018 and networked with KTH Sweden, Electrolux AB, Huawei Sweden R&D, STFC/RAL, Volvo. He is a guest editor of the *International Journal of Refrigeration.* He collaborates with Professor Savvas Tssou at Brunel University, and Professor Richard Stone at Oxford University.

IISPRG created image-processing algorithms for texture analysis of medical CT and MRI scans, which resulted in long-term collaborations with BSMS and a spin-out company: TexRAD Limited, now Feedback plc (see ICS). Feedback Medical gained CE approval for TexRad to be used on non-small cell cancer patients directly; obtaining CE approval led to the licencing and distribution agreement with General Electric Healthcare for TexRAD®. Hence clinical cancer patients benefit from optimised treatment plans that avoid invasive procedures *(TH, TAI)*. IQ-AI Ltd recently gained US-FDA, Korean-FDA and CE approval for the use of IISP algorithms as a kidney stone diagnostic and treatment tool, which has been used on more than 1000 patients internationally, giving them sales in South Korea, USA and Europe. TexRAD metrics are used to guide Lithotripter stone fragmentation therapy. In 2015, TexRad won one of the University's Achieving Impact Awards. IISP is collaborating with the NIHR Global Health Research Unit for Neglected Tropical Diseases to develop a bio-impedance spectroscopy measurement system for the detection of podoconiosis in Ethiopia, alongside Addis Ababa University, Wollega University and Georgia Institute of Technology (see above). The IISP group developed a prototype Electrical Impedance Tomography (EIT) machine and participated in clinical trials at the John Radcliffe Hospital in Oxford; the prototype Sussex MK4 EIT machine successfully detected breast cancer tumours *(TH)*. IISP are working very closely with 2020 Surveillance Ltd using Artificial Intelligence for Person Reidentification (reID) in the context of public spaces security, through projects fully-funded by 2020 Surveillance Ltd. The group is collaborating with BritMedical Ltd,

who are funding a project to detect cancer in CT and MRI medical-scan data using deep-learning neural networks, in collaboration with Indiana University *(TH, TAI)*. The group has also conducted and published research with: University of Shanghai for Science and Technology; University of Macau; Baghdad University of Technology; University of Basra; Tashkent, Uzbekistan. It is are collaborating with many other companies including: Headmapper Ltd.; Photek Ltd.; Acutance Scientific Ltd.; Gunnebo Ltd.; Spiral Scratch Ltd**;** Nigerian Communications Satellite Ltd, Abuja, Nigeria; LymphaTech®, Atlanta, USA. **Young** chairs sessions at – and is on the organising committee of – the annual SPIE conference on Target Recognition and Tracking, and delivered a keynote paper at the SPIE Target Recognition and Tracking XXIX conference. **Birch** was also on the programme committee for SPIE International conferences: Video Surveillance and Transportation Imaging Applications (2014 & 15). On a field trip to Iraq in 2018, **Chatwin** gave a keynote presentation at a workshop "Proper Planning of Development and Construction Starts from the Base Map" on "Digital Mapping using LIDAR for GIS", in addition to several presentations on security, resilience engineering, and medical imaging research. He is also a member of REF Sub-panel 12 and the EPSRC College.

RMSRG: **Glovnea** has strong links with universities in Japan, and industrial research collaborations in Europe with SKF and Mahle. He is an Invited/visiting professor at Kyushu University, Japan (since 2011), and is on the editorial board of the journals *Lubricants* and *Annals of Engineering*. He is a member of the scientific committees for: the International Conference Advanced Concepts in Mechanical Engineering, Lasi, Romania, 2014; International Conference ROTRIB '16/19, Galati, Romania 2016- 2019. Tribology invited lecture: CRRC Zhuzhou Electric Co., Ltd, (part of CRRC Corporation Limited) China, September 2017. **Aviles-Espinosa** collaborates with the University of Texas with whom he developed an advanced drug delivery system *(TH)*. **Rendon-Morales** sits on the EPSRC eFutures 2 steering group – the EPSRC-funded electronics research network. In collaboration with researchers from EU and the NHS Brighton and Sussex University hospitals, she designed an innovative stress-free foetus monitoring system *(TH).* She has been a keynote speaker at the Paediatric & Neonatal Research Symposium 2017 and 2018, and contributed to SoapBox Science Women in Science, Brighton, 2018. **Nguyen** collaborates with: Countryside Services Ltd, Devenish Nutrition Ltd, AES Kilroot Power Ltd., Williams Industrial Services Ltd., and Quinn Ltd., and OPTIMIN "Optimising Energy Management in Industry" *(TSE)*, Tata Steel UK, DPS-Global, Econotherm UK, Ltd., Crowley Energy Ltd, Brunel University, Queen's University Belfast, Cranfield University. In the context of advanced robotic applications, **Yanan Li** has established extensive collaborations with local and international academics, including: HIT, Zhejiang University, Tsinghua University in China, NTU, NUS, ASTAR in Singapore, NTT in Japan, TUM, DLR in Germany and Imperial College. He served as Technical Committee member on Bio-mechatronics and Bio-robotics Systems and on Autonomous Bionic Robotic Aircraft, IEEE SMC Society, and AE, IPC member and Chair for over ten conferences in robotics *(TH, TAI)*.

STRC: In the area of wearable technologies, the STRC contributes to open-access in the community through the creation of numerous reference machine-learning datasets for human activity recognition from wearable sensor data. Many of these datasets have become reference datasets in the community, such as the OPPORTUNITY dataset of activities of daily living, the Daphnet dataset of Freezing of Gait in Parkinson, the Skoda manufacturing activities dataset, and the most recent SHL Locomotion and Transportation Dataset. Furthermore, they lead international activities raising the awareness of these datasets, and the research Centre, through the organisation of international machine learning challenges in the field of human activity recognition using such datasets. STRC organised the SHL Activity Recognition Challenge in 2018 in Singapore (19 teams) and 2019 in London (15 teams), with plans for a 2020 edition in Cancun. **Roggen** was programme committee member for: the annual conference of the IEEE Body Sensor Networks (2017, 2018, 2019); the Ubicomp conference 2016; the International Conference on Wearable Computers (2007 to 2019). He was on the organising committee for the International Workshop on Human Activity Sensing Corpus and Application (2014 to 2019), sponsorship chair for the International Conference on Wearable Computers & Ubicomp (2019), and participated in the British Science Festival (2017). Collaborations in the area of wearable technologies are with: Unilever on consumer behaviour research, Huawei on mobile activity

sensing, University of Linz (Austria), University of Grenoble (INRIA), DFKI (Germany), University of Nagoya (Japan), Ritsumeikan University Kyoto (Japan), Kyushu Institute of Technology (Japan), University of Oulu (Finland), University of Siegen (Germany), Ss. Cyril and Methodius University (Macedonia), Queen Mary University of London, Ritsumeikan University (Japan), Kyushu Institute of Technology (Japan), and others.

Electric Potential Sensor (EPS) technology-driven collaborations include: Plessey Semiconductors (research and licensing); Philips Healthcare (electro-encephalogram using EPS, *(TH)*); British Geological Survey (structural monitoring); Rescon Ltd (DARPA) (through-clothing cardiac monitoring); Meggitt Sensing Systems and Plessey (gas-turbine monitoring, *(TSE)*); Kodak European Research (unshielded EPS applications); Plessey (non-contact control, gesture identification); MOD (electric-fields for position and movement sensing); and the Home Office (forensic fingerprinting). The Group works with the Electronics, Sensors, Photonics and ICT KTNs and a range of key academic collaborators including with: Oxford Institute of Biomedical Engineering (foetal monitoring); University of Sheffield (MRI instrumentation); Cardiff School of Optometry (electro-retinograms); and the Universities of Leicester, Newcastle and Sheffield (radiation sensing). Collaborations in the area of flexible-electronics are with: Corning (flexible-electronics on glass), John Florence (orthotics), University of Bolzano (Italy), and others.

SRG: The group's industrial links are extensive and include: large multinationals, SMEs and government agencies. SRG is developing X-ray fluorescence spectrometers that can analyse seabed mineral resources *in situ*. The instruments are for subsea materials analysis with remotely operated vehicles at depths of ~4km, as well as in production monitoring of seafloor collecting and stockpiling machinery, and in slurry-transfer pipes and inlets. Their research in this area has received significant interest from industry, including from Schlumberger. The group has produced some of the world's highest internal conversion efficiency radioisotope micro-batteries and are working to commercialise the technology, which is expected to be of significant economic and national strategic value. Such high reliability, harsh environment tolerant power sources are required for numerous defence and governmental applications (e.g. for weapons systems, encryption keys and anti-tamper devices), as well as biomedical applications including power systems for neurostimulators to alleviate the symptoms of Parkinson's disease and chronic pain *(TH)*. Two patent applications have been filed and planning is underway for a spin-out company.

A compact spacecraft attitude determination device enables near systems with hemispherical fields-of-view and star tracker level performance in a substantially more compact, lower mass instrument. The Group's contribution in this area has been greatly facilitated by Barnett's Philip Leverhulme Prize, and a patent for the technology has now been filed. Commercial partners (SSTL and Clyde Space) have been secured. A spin-out company is planned. The technology is also useful for missile systems, GPS-denied environment navigation, autonomous shipping, and direction finding in laser-dazzle attacks. The technology will facilitate new commercial and scientific use of space.

TFMRC: Primary aero-engine collaborators have been Rolls-Royce Plc, GE Aviation and MTU Aero Engines AG, with a smaller arrangement with Mitsubishi Heavy Industries for industrial gas-turbine engines. Key academic collaborators include the University of Cambridge; University of Bath; Beijing University, China; Shanghai University, China; and the University of Nantes, France. **Petrov** is on the Editorial Board of the journal *Shock and Vibration*; his keynote lectures include: at 6th Symposium on Mechanics of Slender Structures, Shanghai, 19-20 December 2016; on Nonlinear Dynamics, Vibration, Acoustic and Noise Control at the 4th Annual World Congress of Advanced Materials 2015 (WCAM-2015), May 2015, China. He also organised the mini-symposium "Dynamics of nonlinear structures with contact interfaces" for the 6th European Conference on Computational Mechanics (Solids, Structures and Coupled Problems) (ECCM 6), 2018, Glasgow, UK, and presented four papers at ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition (Oslo, Norway), at which he was a session organizer and chair. Petrov is also a member of the International Advisory Committee for the Collaborative

Innovation Centre for Advanced Aero-Engine of China. Apart from gas turbine research, TFMRC is providing significant support to UK Industry by assisting them to design new products via their ability to use CAD alongside numerical modelling to create and optimise designs; examples include: Aironn Ltd (axial-fan design); Alarko-Carrier Ltd (centrifugal water pump design); Beko plc (muffin baking ovens); Southern Water (water clarifier design); UK Spine KE fund (electronic drug delivery devices for lung tissue). TFMRC were awarded a £28k UKRI Higher Education Innovation Fund (HEIF) Grant to design, CE certify, manufacture, and distribute / sell (not-for-profit) Covid-19 CE certified face-shields to hospitals, care homes, other front-line workers and businesses, in an effort to help protect the public from COVID-19. The group successfully achieved its initial production target was 10,000 shields. Via the above activities, the TFMRC is making a very significant contribution to sustainable living and wealth creation.

Figures 1 & 2 below give an indication of the volume and geographical spread of the unit's collaborations. Figure 3 shows that almost 69% of publications are international collaborations.

Figure 1 Collaborations map, global (2014-2020) (SciVal). Total collaborating institutions: 1,377; total co-authored publications: 1,677.

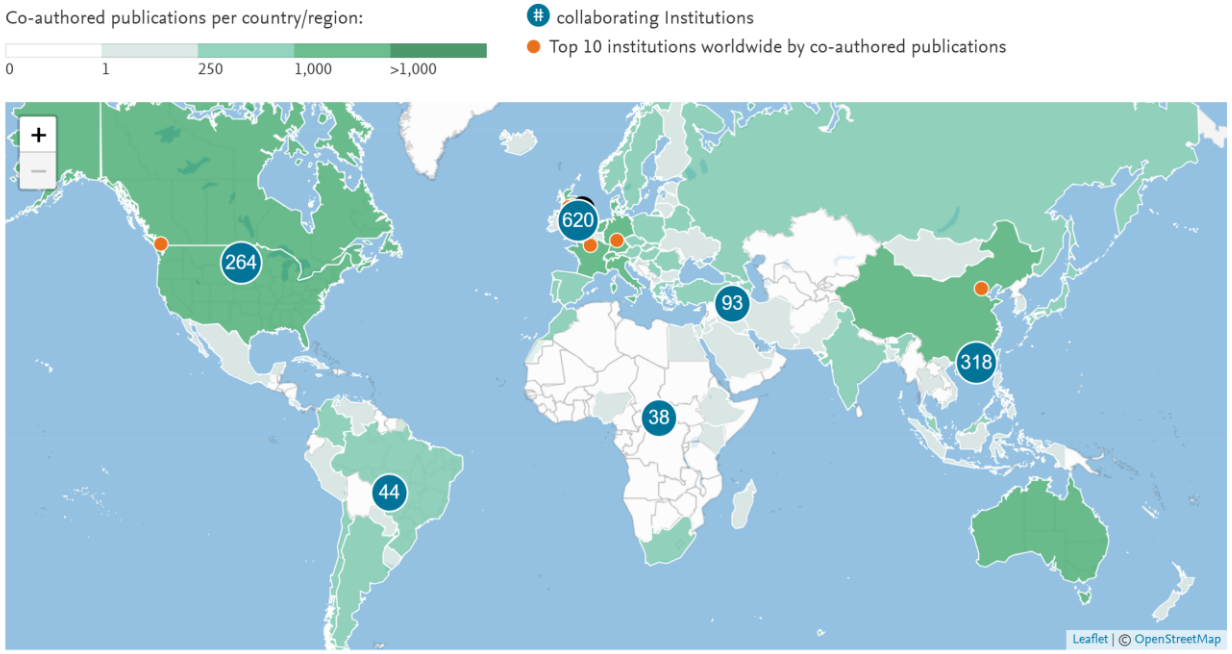


Figure 2 Collaborations map, Europe and Asia (2014-2020) (SciVal)

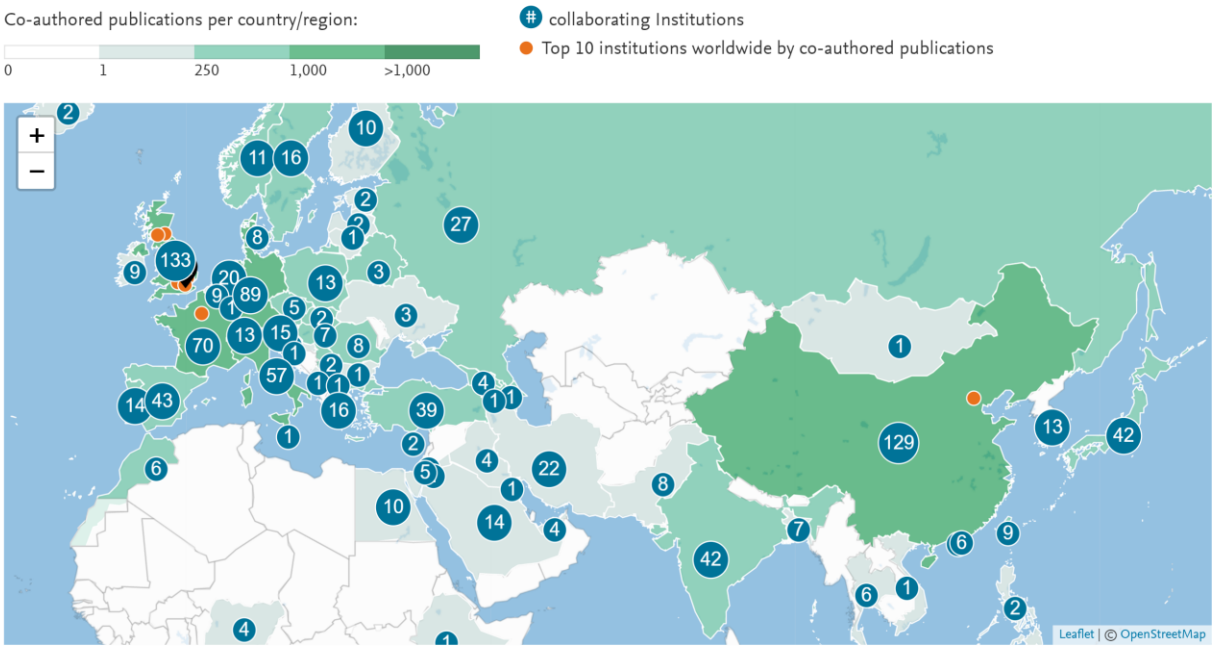
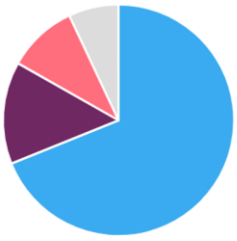


Figure 3 Publication collaborations (SciVal)



Metric		Scholarly Output
International collaboration	68.9%	1,436
Only national collaboration	14.3%	298
Only institutional collaboration	9.8%	205
Single authorship (no collaboration)	7.0%	146