Institution: University of Sheffield

Unit of Assessment: 15 - General Engineering

a. Overview

Automatic Control & Systems Engineering (**ACSE**) is the largest department in Europe dedicated to the study of control and systems engineering. The research in ACSE is organised into three research groups:

- Complex Systems and Signal Processing (CSSP)
- Intelligent Systems, Decision and Control (ISDC)
- Autonomous Systems and Robotics (ASR)

We lead the Centre for Signal Processing and Complex Systems (CSPCS) and the Rolls-Royce University Technology Centre in Control and Systems Engineering (RR-UTC). We are active in seven other University research centres and institutes namely: Institute of Microstructural and Mechanical Process Engineering: The University of Sheffield (IMMPETUS); the Rail Innovation and Technology Centre (RITC); Centre for Signal Processing in Neuroimaging and Systems Neuroscience (SPiNSN); Institute for *in-silico* Medicine (INSIGNEO); Sheffield Centre for Robotics (SCENTRO); Solar Physics and Space Plasma Research Centre (SP^2RC); Sheffield Alcohol Research Group (SARG).

b. Research strategy

1. Vision, strategy and plans

Our vision is to carry out world-leading theoretical and applied research to address challenges posed by the complexity of natural and man-made systems and the demand for higher levels of autonomy and intelligence of future engineering systems. We seek to expand further our portfolio of multidisciplinary research and the level of industrial engagement through the development of technology platforms for a wide range of industries and applications.

To support our vision we structure our research along three strategic research themes – **Complexity**, **Intelligence** and **Autonomy** – as reflected in our group structure. To facilitate collaborations with academics and end-users we established four cross-cutting application areas: **Aerospace & Transport**; **Life Sciences & Healthcare**; **Energy & Environment; Manufacturing & Robotics**.

The specific strategies of each research theme are as follows:

Complexity: Our strategy is to make theoretical advances and develop general methods and algorithms to facilitate the formal modelling, design and simulation of complex engineering, physical, biological and socio-economic systems.

Intelligence: Our strategy is to expand the theoretical foundations and develop practical frameworks and algorithms, enabling the development of intelligent monitoring, control and decision support systems which exploit 'Big Data'.

Autonomy: Our strategy is to pursue research into next-generation autonomous systems and robots which mimic human cognitive capabilities and can operate reliably in complex, unstructured and uncertain environments.

In collaboration with our academic and industrial partners, facilitated by research centres and institutes, we aim to develop new techniques and technologies that address specific challenges and priorities in each of our cross-cutting application areas. Specifically:

Aerospace & Transport: Reduce operating costs, fuel consumption and improve performance through the development of novel technologies for fluid flow control and noise reduction, health and usage monitoring systems, through-life system optimisation solutions, model-based systems engineering.

Life Sciences & Healthcare: Increase the quality, reduce costs of healthcare and address the challenges posed by an aging population through the development of better imaging solutions, assistive technologies and decision support systems. Address the challenges posed by the inherent complexity of biological systems by applying systems engineering methodologies and tools to further our understanding of biological processes and to design and manufacture cell therapies, biologically based parts, devices and systems.

Energy & Environment: Improve the efficiency, autonomy and security of energy generation and distribution, reduce the carbon footprint through the development of key enabling control technologies for smart grids and energy saving solutions. Understand and manage the risks associated with climate change, protect human health and natural environment by developing better models of the terrestrial climate, chemical and radiation pollution, and through the development of advanced technological solutions to monitor the environment and identify precursors for natural disasters.

Manufacturing & Robotics: Increase resource efficiency, flexibility and competitiveness of UK manufacturing through the development of integrated system modelling, simulation and optimisation tools, advanced process monitoring and automation, reconfigurable systems and smart multifunctional materials. Develop enabling technologies for fully autonomous cooperative robots.

To achieve our strategic goals we will:

- Maintain an environment that stimulates creativity, fosters and rewards talented early-career researchers as well as supports the vision of established world-leading researchers (see §c).
- Increase the level of multidisciplinary research and encourage and support innovative, emerging research themes (see §d).
- Build strong partnerships with other world leading academic and industrial organisations that can help us deliver our goals, capitalize on our research and inform our strategy (see §e).
- Ensure that our researchers have the tools, equipment and infrastructure necessary to carry out internationally-leading research (see §d).
- Increase the visibility of our research, facilitate exploitation by our research users, protect and exploit our IP (see REF3).

2. Research achievements since 2008

In line with our plans outlined at the RAE2008, we increased our research capability by strengthening and expanding our research groups through 12 new staff appointments and by investing our own funds in research studentships and equipment (see §c and §d). Overall, since the last RAE, the Department has grown from 18 to 25 academic staff and its annual turnover increased by 26% from £7.9M to £10.0M. We formed new strategic partnerships with Vestas and Network Rail and established new research centres and institutes including RITC and SCENTRO. Our research income has increased by 13% to £2.6M p.a., the number of journal publications p.a. has increased by 24% and the number of PhD awards has increased p.a. by 24%.The EPSRC shaping capability exercise identified ACSE as one of three 'major players' in Control Engineering in the UK.

Complex Systems and Signal Processing. The group is internationally renowned for its work on the identification and analysis of complex spatio-temporal systems, nonlinear signal processing, and the analysis and design of nonlinear systems in the frequency domain. The group is led by Billings, who also heads the multidisciplinary research Centre for Complex Systems and Signal Processing. The Centre has expanded its multidisciplinary activity significantly, leading to the award of over 20 multidisciplinary grants. *Key achievements:* Significant progress has been made in advancing our theoretical understanding of nonlinear systems in the frequency domain [Billings2] (i.e. Billings' Output 2, REF2) and in developing new estimation, analysis and design methods [Billings1,3;Lang1] that exploit the new theoretical results for vibration isolation [Lang2], condition monitoring of wind turbines, railways and in-service Non-Destructive Evaluation (NDE) for nuclear applications [Lang3,4]. The ACSE led BBSRC project "Reverse-engineering Drosophila's retinal networks" in collaboration with the Department of Biomedical Science, produced the most advanced stochastic biophysical model of a Drosophila photoreceptor [Coca2]. Nonlinear system identification and signal processing approaches [Wei1,2] developed under 2 EPSRC grants have been applied successfully to detect, with support from the Ryder Briggs Charity, the onset of epileptic seizures based on EEG signals [Wei3; Billings4], to characterise, under an EPSRC grant, the haemodynamic response at cortical level [Coca2;Wei4] and to elucidate for the first time the functional relationship between solar wind and terrestrial magnetosphere, a problem that was subject for debate since the 1930s [Balikhin2]. Through an EPSRC platform grant we developed a forecasting tool which provides the most accurate two-day-ahead forecast available of electron fluxes at geostationary orbit, which is now used by NASA to mitigate operational risks of spacecraft [Balikhin4]. We developed data processing tools for high-profile space missions including Venus Express [Balikhin1]. Modelling and simulation tools we developed played a crucial role in the discovery of super-hot, super-fast tornadoes, reported in Nature [Fedun1].

Intelligent Systems, Decision and Control. The group is led by Kadirkamanthan who is also Director of the flagship Rolls-Royce University Technology Centre in Control and Systems Engineering. The group is internationally renowned for its work on multiobjective evolutionary optimisation algorithms, intelligent health monitoring and fault diagnosis, decision support systems for biomedicine, information processing, fuzzy systems and computational data modelling. IMMPETUS, of which Mahfouf is Co-Director, involved 12 PDRAs and over 60 PhD students since 2008. Supported by an EPSRC platform grant our collaborations with industrial members of the Centre informed our research, led to a significant number of collaborative papers and produced tangible economic impacts as detailed in §e

and REF3a,b. Harrison led the formation of the strategic partnership with Network Rail and the creation of the Rail Innovation & Technology Centre, which has a focus on intelligent systems engineering for the railways and involves collaborations across the Faculty of Engineering.

Key achievements: We developed new methods to speed up convergence of evolutionary algorithms and improve the quality of solutions to multiobjective optimisation problems [Fleming 1-3] that were subsequently used in control system design and system architecture trade studies for Rolls-Royce and engine calibration for Ford Motor Company. A major achievement of the RR-UTC team was the acceptance and implementation of a design methodology for "the first new radical control law for over 20 years" for the latest fleet of Trent engines that power the flagship Boeing 787 Dreamliner and Airbus A350 aircraft. The innovative optimisation framework Liger, developed by the group, which incorporates the powerful preference-inspired co-evolutionary algorithm [Fleming4] for many-objective optimisation, is currently being evaluated by Ford Motor Company. Supported by MRC and ESRC, Purshouse developed and extended the Sheffield Alcohol Policy Model [Purshouse1,2,3] in collaboration with SARG, which has been central to the international debate over establishing a minimum unit price for alcohol. In biomedicine, intelligent decision support systems for patients in intensive care units [Mahfouf1,3], developed under 2 EPSRC grants, were successfully trialled and won a Medipex Innovation award in 2010. Supported by two EPSRC grants Mahfouf and Panoutsos, created a 'right-first-time' modelling and optimisation framework for manufacturing, based on the concept of 'granular computing' [Panoutsos1]. The framework [Mahfouf2, Panoutsos3] has been used in the manufacturing of fuselage structures, for Boeing, Embraer and Eclipse, and other products. Through an EPSRC grant, we developed new computer tools to assist medicinal chemists in designing new arrays of compounds, expediting the discovery of new drugs. The breakthrough paper [Kadirkamanathan1], which introduced and demonstrated the first quantitative modelling framework of conflict dynamics using data from Wikileaks on the Afghan War, won the 2012 PNAS Cozzarelli Prize.

Autonomous Systems and Robotics. This group, formally established in 2013, is an outcome of the Departmental plan set out in 2009 to achieve critical mass in this strategic research area through the steady investment in people (6 new appointments) and facilities (850m^2 research labs; see §e). Since its formation, the group led by Veres, has secured ~£1M for research equipment and infrastructure and won numerous EPSRC research grants, as detailed in §d. Industrial collaborators include Thales, BAE Systems, National Nuclear Labs, Sellafield, Schlumberger, KUKA, Rolls-Royce, National Grid, Alstom, National Instruments and Texas Instruments. The group members are actively involved in the Sheffield Centre for Robotics, which involves researchers from across the University, providing a truly multidisciplinary environment for robotics research. *Key achievements:* Zhong co-invented the synchronverter technology [Zhong2] and proposed an architecture for the next-generation smart grids which opens the prospect of achieving completely autonomous operation of power systems. Fundamental research in robotic swarms [Gross1,3] and reconfigurable robots [Gross4], currently funded by an EPSRC first grant award, was showcased at the Gadget Show Live in Birmingham and featured on BBC News and Reuters websites. Veres pioneered the world's first natural language programming environment and publication tool for machines [Veres1], which was used under an EPSRC grant to define architecture solutions for reconfigurable rational agents. It was reported on EuroNews, newspapers and magazines. Through 2 EPSRC grants, we developed self-reconfiguring autonomous system architectures; we investigated the distributed frame alignment problem for multi-agent systems with missing or unreliable attitude sensors and established new theoretical results. We also developed computationally light, formation control algorithms for resource-limited spacecraft to be used by ESA's Proba-3 mission [Veres3].

c. People:

1. Staffing strategy and staff development

We aim to recruit and support academic and research staff with the potential to produce world-leading research that shapes and delivers on our three research themes and supports the needs of our industrial partners and other end-users.

Recruitment strategy. We recruit researchers at the forefront of their discipline to lead strategic research areas. We aim to broaden the research portfolio, and to secure the vitality, sustainability and agility of our research groups, through the appointment of high-calibre new academics who have the vision, ability and enthusiasm to shape future national and international research agendas. Our recruitment strategy is exemplified by the new appointments. Specifically:

CSSP: We appointed Wei to strengthen the multidisciplinary research collaborations in Life Sciences &

Healthcare; he established a new collaboration with NHS consultants and developed new tools for detecting the onset of epilepsy. Jones was appointed to develop our flow control capabilities; supported by an EPSRC first grant award he leads the "Wind Turbine Gust Prediction" project in collaboration with Vestas. Esnaola was appointed to strengthen capability in information theory and cyber security and Fedun to expand our modelling and simulation capability. These appointments help deliver our research goals in the Aerospace & Transport, Environment & Energy cross-cutting application area.

ISDC: Purshouse was appointed to sustain our world-leading research in evolutionary multi-objective optimisation and to support strategic growth in modelling and analysis of socio-economic systems; he is an ESRC future research leader award holder, pioneering the use of complex systems methods for predicting population consumption of alcohol. Pope was appointed for his seminal work on meta materials; he leads an EPSRC project on active meta materials for vibration control. Panoutsos was appointed to strengthen our 'Right First-Time Manufacturing' research agenda in collaboration with TWI, TATA Steel and Airbus whilst Trodden was appointed to expand research activities related to control and optimisation of power and energy systems (Energy & Environment cross-cutting area).

ASR: To establish this new group we appointed two research leaders: Veres for his contributions to the theory and application of autonomous systems and Zhong for his seminal research and industrial expertise in next-generation autonomous power grids. Our research capability in this area was also strengthened by the recruitment of four new academics: Gross and Kolling specialize in swarm/collaborative robotics; Gross leads an EPSRC project on the evolution of robotic life forms. Liu is working on formal methods for control of cyber-physical systems, supported by an EU FP7 award. Anderson is pursuing bioinspired robotics and control of biological systems; he is participating in multi-disciplinary projects supported by EU and EPSRC.

Staff Development and Support. We promote a vibrant research culture which stimulates our staff to broaden and deepen their skills and experience, seek out multi-disciplinary opportunities, and develop their research careers in promising directions. The annual Staff Review and Development Scheme (SRDS) provides all staff with the opportunity to reflect and receive feedback on their achievements, set objectives that are aligned with the Departmental Strategy and identify training and development needs required to achieve these objectives. SRDS is also used to discuss career development and aspirations. We reward excellence by nominating staff for discretionary awards, and promotion (3 promotions to Professor, 2 to Reader, 4 to Senior Lecturer). We use a workload model that balances research, teaching and administration; staff with significant research commitments have a reduced teaching and administration load. The Department facilitated 4 staff to take year-long Sabbatical leave. From 2012 the Faculty of Engineering committed an annual budget of some £840K to create a research hub to raise awareness of developments in the research-funding and industrial-funding landscape and to develop external partnerships and funding proposals. The hub has 9 staff: 4 supporting grant applications, 4 supporting industrial partnerships and 1 working with the University's Researcher Professional Development Team to support staff on fixed-term research contracts. This allows academic staff to focus on building the quality and sustainability of their research.

Postdoctoral researchers: The HR Excellence in Research award from the European Commission in 2012 reflects that University departments provide a high quality research environment for PDRAs and are committed to the 7 principles set out by the UK Concordat for the Career Development of Researchers. We develop our research staff through the 'Think Ahead' programme of skills training and career mentoring, and to which 3 academic staff contribute as mentors to PDRAs in other departments. All our research staff have access to a broad range of training and development programmes that are coordinated by a Research Development Manager and map to the Vitae Researcher Development Framework. All training needs identified via SRDS are collated so that the programme can respond to identified needs. The Department provides bridging funds to ensure a smooth transition between research projects. 5 Professors and 3 new academics began their careers as PDRAs in ACSE.

New academics: Each newly appointed lecturer receives start-up funding and a reduced teaching and administrative load for the first two years. The Department funds a PhD studentship for each successful first grant application. Lecturers are set demanding probationary targets for research and are supported in achieving these, whilst successfully balancing other academic demands, through an advisory team including a mentor, research group leader and Director of Research. We established a bespoke proposal peer-review process which helped Anderson, Gross, Jones, Liu, Pope and Wei to secure EPSRC/ERC/EU funds. Purshouse won an ESRC Future Research Leaders grant award.

Research leaders: We develop research leaders through The Sheffield Leader programme for which the University has been shortlisted in 2013 for the Times Higher Education (THE) award 'Outstanding Contribution to Leadership Development'. Personal fellowships were won by Coca (MRC) and Zhong (EPSRC and RAEng).

Equality and Diversity: The Department is comprised of staff from a variety of cultures around the world making it an exciting and diverse place to work. The key diversity challenge for us, and for the engineering profession as a whole, is to attract, retain and develop excellent female engineers. In partnership with other Faculty of Engineering Departments, specifically through the Women in Engineering Initiative, we are taking positive actions and making investments to increase the number of female academics, researchers and students. The Department has recently appointed its first female Reader, following a recruitment campaign that included positively worded advertising and used targeted media to attract female applicants, alongside mainstream advertising routes. Senior recruiting managers have undertaken "unconscious bias" training, and this is to be extended to all recruiters as part of a Faculty-wide programme. Our demographic profile, 46%UK, 25%EU, 29%non-EU, is further evidence to our commitment to equality and diversity.

Visiting Scholars: We view academic exchange programmes as a key facilitator of staff development and multi-disciplinary research collaborations. Our focus is on strengthening collaboration with EU, US and the BRIC economies. We participate in the 111 Project (China), BOYSCAST Programme (India), Royal Society International Exchange Scheme, British Council UKIERI Research Project, and EU FP7 International Research Staff Exchange Scheme, the latter involving world leading academics in optimisation and control from Brazil, Mexico, Canada and Israel. During the assessment period, over 30 esteemed academics visited and collaborated with ACSE academics for periods of up to a year including: the Associate Vice Chancellor for Research at the University of California, San Diego, Prof. M. Krstic and the Deputy Director of the Indian Institute of Technology Bhubaneswar, Prof. G. Panda.

2. Research Students

We place particular emphasis on the recruitment and training of PhD students. We have a highly selective recruitment policy which ensures the students have the right background, skills and research abilities to undertake challenging research projects. In addition to 2 EPSRC DTA awards p.a., we fund two full research prize scholarships opened to overseas students and a number of full and partial fee scholarships. Since 2008 we have invested over £700K of our own money to support PhD students. Each student receives guidance and direction from a supervisory team made up of at least two academics. All PhD students are allocated workspace, a new computer and have access to scientific software and to comprehensive research resources. The Department runs a vibrant seminar series and has established the annual Harry Nicholson Distinguished Lecture in Control Engineering.

We were the first department in the University to implement a cohort-based Doctoral Development Programme that provides a flexible training plan, tailored to the individual needs of the students. As part of the programme, all research students complete 12 weeks of training on subject-specific topics, research ethics and a wide range of transferable skills. Annually, students complete a Training Needs Analysis (TNA), which is an assessment of their current skills and a training plan for the year ahead. The TNA is used to identify additional training and development activities tailored to the needs of each student. Progress reports by staff and students are submitted to and monitored by the PGR Tutor and the Graduate School. All students undergo a 'Confirmation Review' (report and viva examination) after one year. PhD students attend departmental seminars and have access to a £20K annual travel budget for conferences. The Department runs an annual Postgraduate Student Symposium which brings together more than 100 PhD and MSc students as well as industry representatives. Awards won by our PhD students include: Zammit-Mangion for the best IET Control Dissertation Award in 2012 and also lead author of the 2012 PNAS Cozzarelli Prize winning paper; In 2009, Li and Chu for the Chinese Government Award for Outstanding Self-financed Students Abroad ($5K); Giagkiozis for the Franklin V. Taylor memorial award for Best Paper at 2013 IEEE Int. Conf. Systems, Man, and Cybernetics.

d. Income, infrastructure and facilities

1. Income

ACSE's reputation for world-leading research is reflected by its funding portfolio. In the assessment period we won 115 grants totalling £15.4M (apportioned grant value), of which RCUK £9.6M, Industry £2.3M, EU Framework £2M, Charities £419K, EU (Other) £532K, Government £355K, Overseas £117K. Research income p.a. has grown by 13% to £2.6M. Overall, the research application success

rate for the Department was 35%. Highlights include two five year awards: renewal of a £1.2M EPSRC platform grant and the award of a prestigious €1.95M ERC Advanced Investigator Grant. Since its formation, the *ASR* group has demonstrated its vitality by leading or contributing to 5 EPSRC grants totalling £10.9M (project value) on reconfigurable autonomy, distributed multi-agent autonomous systems, smart grid technologies, infrastructure monitoring and future vehicles. Knowledge transfer activities and consultancy services were delivered mainly through smaller (<£100K) industry funded projects and through KTAs, KTPs totalling £1.3M. We delivered training for World Health Organisation and Rolls-Royce. The research awards and investments provide ample support for our groups to achieve their strategic research goals in collaboration with academic and industrial partners.

2. Investments in facilities and infrastructure

£1.6M has been invested in a state-of-the art *Control and Power Systems Lab*. We have established four further laboratories: a *High Performance Computing Lab* equipped with £150K FPGA, GPU, SpiNNaker hardware; a £110K *Autonomous Control Lab* featuring autonomous rovers, quadrotors and miniature spacecraft; a *Natural Robotics Lab* featuring more than 160 swarm and self-assembly robots; a *Biomedicine Lab* featuring BioSemi, Finapres, Datex analysers and a NIRx diffuse optical tomography system for monitoring neuromuscular transmission and haemodynamic responses. We gained new space for postgraduate and postdoctoral researchers (130m^2), refurbished 370m^2 of research accommodation (£150K) and refurbished and equipped 260m^2 of research labs (£500K).

3. Access to shared and central facilities

We have access to the University-run High Performance Computing (HPC) facility, in which the University invested £2M over the REF period, and the N8 Tier 2 HPC facility in which the University is a partner. In partnership with Universities of Leeds and York and with £644K EPSRC support, ACSE has expanded the capacity of the shared White Rose Grid e-science centre. In the REF period we also had access to European Space Agency shared facilities valued at £2.8M.

4. Future investments

As part of the 2013 EPSRC Great Technologies Capital Calls, ACSE secured £350K for research equipment in Robotic and Autonomous Systems (£1M project value) and £450K for Grid-scale Energy Storage (project value £4.8M). The awards will be used to expand the Autonomous Control (e.g. KUKA robots & manipulators, autonomous rovers and quadrotors) and Natural Robotics Labs (800 swarm robots) as well as the CAPS laboratory (real-time digital simulator). The new £21M Engineering Graduate School, which will host ACSE's new 750m^2 facility for robotics research, will open in January 2014. A new 19,500m^2, £94M Engineering Building will be finished in 2016 and a further £47M will be invested to refurbish the existing engineering complex, providing us with additional research facilities.

5. Future income plans

Over the next period we will increase our share of Industrial, RCUK and EU funding through strategic collaborations with world-leading academic institutions and users of our research. Specifically, In *Aerospace & Transport* we will engage with Airbus, Boeing, Rolls-Royce and other academic institutions through the Aerospace Research Institute which is supported by £2B for the next 7 years. In collaboration with Rolls-Royce, Ford Motor Company, Jaguar Land Rover, and Tata Motors we will expand our funding portfolio in systems health monitoring, through-life system optimisation and design.

In *Manufacturing & Robotics* we will work with the Advanced Manufacturing Research Centre with Boeing, which has secured £43M to create the Factory 2050 facility, to secure funding under relevant EPSRC and EU Horizon 2020 programmes (e.g. Factories of the Future). With key industrial partners (e.g. BAE Systems, Nuclear Labs, Thales) we will grow our income for robotics-related research.

In the *Energy & Environment* area we will capitalise on our recent investments in people and infrastructure; in collaboration with Vestas, National Grid and Alstom we will secure grants (EPSRC, Horizon 2020) to develop Smart Grid Management solutions and to improve wind turbine efficiency.

In *Life Sciences & Healthcare*, in collaboration with biologists and the NHS, we will secure funding (RCUK, EU, Charities) for multi-disciplinary research we have initiated and funded, for example in real-time diffuse optical tomography, EEG data analysis, personalised therapeutic approaches and stem cell therapy manufacturing. Overall, our research groups have an excellent track record in securing funding to deliver the research strategy and goals outlined in §b.1.

6. Provision and operation of specialist infrastructure and facilities

Virtual Reality Simulator: We operate an advanced virtual reality facility originally developed for flight simulation, which we plan to expand to support our research in Autonomous Systems and Robotics.

The simulator has a flexible modular architecture, which enables the models, displays, control laws and visual system to be re-programmed for a wide range of applications, enabling research in control system design, sensor fusion, distributed control architectures, multi-agent autonomous systems.

The Control and Power Systems Lab: This is a state-of-the art (100m^2), highly reconfigurable facility equipped with a microgrid, energy storage, controllers and instrumentation, which is used for fundamental and applied research in control and energy management strategies for vehicle power systems, power grids and energy storage in collaboration with research users e.g. National Grid.

e. Collaboration and contribution to the discipline or research base

1. Collaborative & Interdisciplinary research

Research collaborations are a cornerstone of the Department, Faculty and University research strategy. Interdisciplinary research is nurtured by each research group and is facilitated by strategic initiatives and projects coordinated by cross-cutting research coordinators and by research centres and institutes. Existing and future strategic interdisciplinary initiatives and new collaborations are supported by a £2M Departmental strategic reserves fund. The Department also benefits from a share of additional Central Faculty and University strategic level support and commitments which amounted to £6.44M over the period. Collectively, we published 577 collaborative outputs (57% of all research outputs) with 265 organisations from 44 countries. Out of these, 207 were HEIs (37 UK, 170 from 39 other countries) and 58 were other organisations from 10 countries. We participated in 50 collaborative grants, involving other departments or institutions, representing 43.48% of all grants awarded.

Exemplars of multidisciplinary research supported by research centres. *CSPCS***,** which brings together 20 academics from very diverse research disciplines, facilitated and supported multi-disciplinary research collaborations involving over 30 PhD students (12 supported by the Centre), generated over 100 multidisciplinary publications, leading to 20 multidisciplinary grant awards since 2008, totalling £13.3M (awarded project value). *Exemplar international projects:* The flagship project Human Frontier Science Program (HFSP) Grant “Stem Cell Dynamics in Time and Space” ($USD900K) involving ACSE & Biomedical Science from Sheffield and the University of Melbourne, is applying control theory to understand the dynamic mechanisms that govern stem cell fate choice. The EU FP7 project (€3.3M) "Demonstration of methods and tools for the optimisation of operational reliability of large-scale industrial wind turbines – Optimus" involves ACSE and 10 other partners.

Exemplar national projects: The ACSE led BBSRC project “FPGA supercomputing technology for high-throughput identification and quantitation in proteomics” (£430K) in collaboration with University of Liverpool, produced the world's first FPGA co-processing solution for tandem mass spectrometry. We participate in the ground breaking £4.9M EPSRC funded project “Biologically-Inspired Massively Parallel Architectures – computing beyond a million processors” in collaboration with Manchester, Southampton, ARM Ltd and Silistix Ltd.

Exemplar local projects: We helped secure the EPSRC Frontier Engineering grant (£4.86M) “Modelling complex and partially identified engineering problems – Application to the individualised multi-scale simulation of the musculoskeletal system”, involving academics from across the Engineering Faculty (2 from ACSE) and the Medical School. An on-going (£311K) NERC funded research project, involving academics from CSPCS and Geography, uses modelling tools developed in ACSE to identify the causes for the accelerated breakdown of Greenland’s ice sheet over the last 10-15 years.

SPiNSN supported research produced new models of neural and haemodynamic signals, algorithms for detection of epileptic seizures and diffuse optical tomography. An exemplar project is the recently awarded £600K BBSRC grant involving 2 academics from ACSE and 5 from Psychology.

SP^{2}RC facilitates the application of analysis, modelling and simulation methods developed within ACSE to problems within the field of Space Plasma Physics. We were co-investigators on the €85M Venus Express mission, the first European spacecraft to visit planet Venus. Data processing tools developed under 2 STFC grants enabled the remarkable discovery reported in Science that magnetic reconnection happens on Venus. ACSE led the EU FP7 project “Search for Electro-Magnetic Earthquake Precursors combining satellite and ground-based facilities”, involving 3 Institutes of the Russian Academy of Sciences and the Centre National de la Recherché Scientifique.

Exemplars demonstrating the scale and reach of industrial research collaborations and how these collaborations informed our research. *IMMPETUS*: In collaboration with 28 industrial companies we develop and apply systems engineering tools and methodologies to improve metal processing. The Centre facilitated research collaborations with TWI, Airbus and TATA Steel, involving

10 PhD students, which produced 91 publications and one patent. The intelligent system which informs the optimal selection of Friction Stir Welding (FSW) parameters, developed under 3 EPSRC and 1 METRC grants totalling £5.4M, is now routinely used by TWI for joining high strength aluminium alloys for commercial clients including Embraer, Boeing and Eclipse and contributed to the new technical standard ISO-25239 for FSW published in 2011. Our manufacturing research strategy (detailed in §b) is largely driven and informed by the needs of the long-term industrial collaborators.

RR-UTC: The Centre has a programme of 15-20 medium-term projects underpinned by a programme of more generic, longer-term research. Supported by £2M, RR-UTC produced significant economic impact as well as 75 outputs covering three main areas: advanced control, architectures and systems, health management technologies. The Centre's staff and postgraduate students (15 PGRs) engage with engineers at all levels within Rolls-Royce through quarterly management meetings, annual reviews and workshops hosted by the company. Through these mechanisms we identify technological requirements and challenges, which allow us to align our research strategy to meet their research needs.

2. Contribution to the advancement of the discipline and vitality of the research community

National Exemplars: In 2008 Zhong and Coca co-founded and coordinated New-ACE, the EPSRC Network for New Academics in Control Engineering aimed at strengthening the UK control engineering research base through better interaction and cooperation between early stage academics and researchers in the field. New-ACE organised 6 thematic workshops attended by 142 participants and 50 invited speakers. The network, which now has 178 members (20 international), has since been integrated into the UK Automatic Control Council.

International Exemplars: Zhong was funded by EPSRC under the International Collaboration Sabbaticals scheme to foster long-term collaborations with leading experts in control and power electronics in the USA from 2012 to 2013. He visited over 20 universities, 4 NSF research centres and 2 DoE national labs, delivered 5 workshops at international conferences and received 4 plenary talk invitations at international conferences. Leading experts M. Krstic, M. Vidyasagar and R. Murray also visited the Department as part of this project. Fleming was joint lead of the International Research Staff Exchange Scheme on New Horizons for Multi Criteria Decision Making involving world leading researchers from Canada, Brazil, Mexico and Israel. Kadirkamanathan leads the collaboration with IIT Kanpur in integrated sensing, monitoring and healing under a British Council UKIERI award.

3. Leadership roles

9 staff were involved in 17 international advisory, funding or standards bodies including: Fleming appointed (for life) the only UK-based Adviser to the International Federation of Automatic Control; Zhong is the UK representative for the European Control Association and External Advisor in the Italian Evaluation of Research Quality exercise; Mahfouf is Advisor to the Algerian Government's High Education Ministry and Sonatrach Oil Company; Veres chaired the IFAC Technical Committee on Adaptive and Learning; *11 staff were involved in 10 national advisory, funding or standards bodies including:* Fleming was a member of the UK Research Assessment Exercise 2008 and is Lead Assessor for EEE Standing Committee for Research and Secondment Schemes Royal Academy of Engineering; 7 staff are members of EPSRC (6) and ESRC (1) Peer Review Colleges.

4. Dissemination and knowledge exchange

Workshop and conference organisation: *ACSE staff supported the delivery of over 150 national and international conferences, symposia and other meetings as* conference chairs/co-chairs (8), workshop organisers (10), IPC Chairs (5), members of organising committees/advisory boards (5) or as IPC members. Highlights include the 4th Int. Conf. on Pattern Recognition in Bioinformatics (2009) and the 7th Int. Conf. on Evolutionary Multi-Criterion Optimisation (2013), which we organised and hosted.

Invited and keynote lectures: ACSE delivered over 155 invited lectures and presentations, including 16 plenary or keynote addresses, at conferences and meetings. **Editorships:** 6 staff are Editors-in-Chief, 9 staff are Associate Editors for 11 journals, 4 serve as members of 4 Editorial Advisory Boards, 4 staff were Guest Editors for 6 Special Issues and 4 are members of Editorial Boards for 10 journals.

5. Awards, prizes and honours. Fleming: elected Fellow of the International Federation of Automatic Control (2009); Kadirkamanathan: 2012 PNAS Cozzarelli Prize in Engineering and Applied Sciences; Mahfouf: Medipex Innovation Award (2010); Zhong: appointed IEEE Power Electronics Society Distinguished Lecturer (2013); Highly Commended Certificate at the IET Innovation Awards (2009).