Institution:	**Imperial College London**
Unit of assessment:	**13A – Electrical & Electronic Engineering**

A. CONTEXT

Research in the Electrical and Electronic Engineering (EEE) Department comprises a balanced mix of theoretical, analytical and experimental work, with particular emphasis on theme-based interdisciplinary collaborations within the strategic priorities of Imperial College. The profile reflects the pervasive nature of our subject in different branches of engineering and science, while acknowledging the important role it has in securing the economic strength of the UK, in tackling key global challenges in healthcare and energy, and in enabling improvements in the well-being and the quality of life of people in the UK and elsewhere.

The Department conducts research in the major areas of electrical and electronic engineering through five research groups: Control and Power (CAP), Circuits and Systems (CAS), Communications and Signal Processing (CSP), Optical and Semiconductor Devices (OSD), and Intelligent Systems and Networks (ISN).

The beneficiaries of our research fall broadly into the following categories:

Industry: The most significant stakeholders in our research are from the industrial sector, benefiting through solutions to key industrial challenges [case studies 1, 2, 5], through creation of spinout companies offering new products and services [case studies 2, 3, 4] and through patenting and licensing of new IP [case studies 3, 4]. Over the REF period (2008-2013) we have engaged in collaborative research programmes with 84 separate industrial organisations and provided technical consultancy to 83 different clients. Staff members have also been involved in founding and/or developing 9 spinout companies.

Government and Regulatory Bodies: We work in close collaboration with various government organisations such as MOD, DSTL and Ofgem, directly contributing to their research and development, and influencing government policies and regulatory guidelines, particularly in the energy sector [case study 5].

Health Services: Technology for Healthcare is one of the main topics of interdisciplinary research in the Department. Many of our designs and research outcomes have been employed to improve the health and the quality of life in patients [case study 3]. Over the REF period, we have worked with clinicians and medical researchers in 15 different hospitals.

Financial Sector: Our research has had both direct and indirect impact in the financial sector. Algorithms from our work in signal processing and stochastic control have been used extensively in modelling financial systems and pricing of energy. Work in high performance computer systems has been deployed for financial risk modelling and management [case study 4]. The indirect impact is achieved through the training of our PhD graduates who have found employment in the financial sector because of specialist expertise and knowledge in mathematical modelling and analysis acquired and developed through their research training.

The Public: In order to raise the profile of, and enthusiasm for, science and engineering among the general public, those members of staff presented with opportunities to disseminate their research to the public have embraced this with vigour. The results of our research have been exposed through public broadcasts on national TV and radio on multiple occasions [case study 2].

B. APPROACH TO IMPACT (2008-2013)

Throughout the current REF period, the Department has made maximising the impact of its research on industry, government, the health sector and the wider community a key priority. This is in accordance with Imperial's publicly stated mission: "*To develop our range of academic activities to meet the changing needs of society, industry and healthcare.*"

We have established a culture within the Department in which the importance attached to impact is fully understood by all staff. Actual and potential impact is one of the criteria considered in our processes of staff recruitment, development, appraisal, reward and promotion. The approaches and mechanisms we have taken to create and promote impact include:

B.1 Engagement and collaboration with Industry

Over the REF period our staff have engaged in collaborative research programmes with 84 separate industrial organisations. Of these, 40 are from the UK, 29 from Europe, 12 from the US and 3 from the rest of the world. The types and sizes of companies encompass a wide range and include:

- Large multinational companies such as: Airbus, BAE Systems, General Dynamics, GlaxoSmithKline, IBM, Samsung and Siemens;
- UK based utility companies such as: BT, EDF Energy, National Grid, Scottish Power and UK Power Networks;
- UK and EU based high-tech companies such as: Bang & Olufsen, Imagination Technologies and Oxford Instruments;
- UK based SMEs and start-up companies such as: Barnard Microsystems, DNA Electronics, Microsaic, Nexeon, Drayson Wireless and PPA Energy.

Senior engineers and managers from twenty leading companies based in the UK are members of our Industrial Advisory Group; these include Rolls-Royce (*Kevin Daffey, Head of Electrical Power and Control Systems*), Cobham (*Steve Nightingale, Chief Consultant*) and Thales (*Chris Firth, Chief Scientist*). The Group meets twice a year to provide inputs to our strategy development in research and education, and for us to inform them of the latest research trends. As part of the Spring meeting, we hold an annual research poster competition in order to showcase our research to our industrial partners and to provide them with an opportunity to explore potential collaborations. The best poster judged by a selection panel is awarded the Eric Laithwaite Prize.

B.2 Intellectual Property Generation

We encourage our researchers to pursue IP generation and exploitation in collaboration with **Imperial Innovations**, a publicly listed company specialising in technology transfer, company incubation and investment with whom Imperial College has a pipeline agreement covering the exploitation of IP.

With the help of Imperial Innovations, the Department has participated actively in intellectual property generation, protection and exploitation. The success of our intellectual property generation strategy is supported by the following evidence:

- Since 2008 and based on our research, our staff have published 55 separate families of patents (i.e. parallel filing of a patent in separate domains counts as one). The majority of these have been assigned or licensed to external companies such as Alstom, DNA Electronics, Drayson Wireless, Maxeler, Microsaic, Nexeon and Toumaz.
- IP generation is embedded in our research culture; 60% of staff members listed in REF 1 (27 of 45) are named inventors in one or more of the 180 separate patents that have been published. Most of these are being assigned to, licensed to, and/or exploited by industrial companies worldwide.

B.3 Knowledge Transfer through Spinout Companies and Consultancies

Staff members have been actively supported by the Department to exploit their inventions through spinout companies. This support includes staff being given time and space to operate their spinouts in the early stages. Through Imperial Innovations, some spinouts have also

received seed funding. Since 2008 our staff have founded and/or developed 9 start-up companies: DNA Electronics, Drayson Wireless, Ervitech, GeneOnyx, Microsaic, Nexeon, NovoCore, Toumaz and Bboxx. Microsaic and Toumaz are publicly listed and have a combined market capitalisation of £83.6M (16 October 2013). In the REF period our staff and their start-up companies have won 21 separate industrial awards and prizes for their contributions to industry.

Knowledge transfer to industry through consultancies is facilitated by Imperial College's wholly owned subsidiary, **Imperial College Consultants** (ICON). Over the REF period, our staff have engaged in 122 separate consultancy contracts involving 83 different organisations and generating a total of £4.58M in consultancy income. As an example, the electrical equipment company Alstom Grid committed to a new product development and demonstration in the area of high-voltage DC transmission as a consequence of consultancy (by Green) on modular power converter optimisation.

B.4 Influencing Policies of Governments and Regulatory Bodies

Due to the close links we have established and maintained with numerous UK Government-run organisations, our research has had direct impact on their technology strategies over the current REF period. Examples are forensic speech research with the Home Office and GCHQ, the MOD sponsored Defence Technology Centres (SEAC DTC and Data Fusion DTC), and the University Defence Research Centre (UDRC) in Signal Processing with MOD and DSTL.

Our staff have participated in and influenced government's regulatory policies through the provision of scientific inputs to regulatory agencies such as the Energy Regulators and the Office for Gas and Electricity Market (Ofgem). They have also acted as scientific advisors to House of Commons Select Committees, the Government Chief Scientific Advisor and DTI's Foresight Committee.

The impact of our expertise extends beyond the UK. Since 2008, our staff have represented the UK's interests and perspectives at, and provided technical inputs to, international agencies including the International Energy Agency, the International Atomic Energy Agency, the International Council on Large Electric Systems, the European Commission, National Science Foundation and the Singapore Government International Advisory Panel on Medical Devices.

B.5 Targeting Improvements in Health and Quality of Life

The Department has strongly promoted health-related research as one of our priorities for the past decade. To ensure genuine impact of our work in the healthcare sector, we have followed a deliberate policy of working closely and directly with clinicians in hospitals. Since 2008 a number of our electronic systems have been deployed in experimentation, at clinical trials, or as aids to treatments in 15 hospitals. These include some that are part of Imperial College (e.g. Hammersmith, St Mary's, Royal Brompton), some elsewhere in the UK (e.g. UCH, King's College Hospital, Oxford University Hospital) and some overseas (e.g. Centre for Neurophysiology and Clinical Physiology, Mannheim in Germany, St. John's Health Centre, Santa Monica in USA, and Ospedale San Raffaele, Milan in Italy). Our staff have worked within these hospitals and clinics with 42 clinicians and medical scientists.

B.6 Generating enthusiasm and interest in Science through Public Engagement

Our staff are encouraged to engage with the public in disseminating the outcomes of their research. Since 2008, we have participated in BBC broadcasts including "Sky at Night", "Hardtalk", "Click", "Richard Hammond's Engineering Connections" and "How to put a human on Mars" as well as multiple appearances on BBC Radio's "Today Programme". We have also participated in public engagement events held at the Science Museum.

Each year, the Department presents three to four exhibits at the Imperial Festival demonstrating the relevance of our research to society. This two-day Festival held in May is open to the public and annually attended by around 5,000 people.

The Department hosts three distinguished public lectures every year (the Dennis Gabor Lecture, the Peter Lindsay Lecture and the Alec Reeves Lecture), covering diverse topics ranging from space, defence, integrated-circuit designs and plastic electronics. These events are always well attended, attracting an audience of between 150 and 300 at each lecture, promoting the excitement of science and engineering.

C. STRATEGY AND PLANS

Our strategy is to achieve ever increasing levels of impact from our research portfolio through all available avenues including the following:

- Actively encourage and promote staff secondments to industry, and to seek industrial sponsored Chairs and Fellowship positions;
- Develop a departmental strategy to promote our research through creation of focussed research centres, acting as "shop-windows" and publicity outlets for our research;
- Employ Prof Phil Sutton, former Director General, Science and Technology Strategy MOD, to chair the Industrial Advisory Group and to help further develop our strategy for impact;
- Leverage the newly acquired 22.7 acre Imperial College campus in west London, housing the £150 million Research and Translation Hub (completion 2015), to facilitate staff in achieving maximum impact from their research, and to support fledgling spinouts, including DNA Electronics that is already committed to move there.

We have identified a number of recently successful areas of research with strong industrial-transfer potential that are likely to come to fruition over the next REF period, and at which we will direct future efforts. Three of these areas are:

- **Biomedical circuits and systems** – this continues to be a thriving and successful area generating new inventions (15 patents published since 2010) and investments. One such example is Toumazou and Bloom's recent award of the ERC Synergy Grant (€7.2m) to develop an electronic implant to treat obesity (i2MOVE).
- **Energy related research** – this encompasses the works of 10+ staff members on energy harvesting, wireless power transfer, smart-grid, e-storage technologies and power electronics. The group has recently filed 10 patents in this area and received considerable funding support from industry, research councils and the EU.
- **Security and Utilities** – this multidisciplinary research area incorporates works from several groups, CAP, CSP and ISN, to deal with the security of electricity supply in the context of cyber physical systems.

D. RELATIONSHIP TO CASE STUDIES

The Department has submitted five case studies in five distinct areas of research. Together they provide evidence of the effectiveness of our approaches and mechanisms to impact described in Section B above (B.1 to B.6), as referenced in brackets.

Case study 1 in **model predictive control** demonstrates how our research in control engineering has been deployed by numerous multinational enterprises such as Honeywell and ABB and has improved industrial processing in many areas, including manufacture of cement products and high value-added chemical processing [B.1].

Case study 2 in **microengineering** demonstrates how our research in 3D silicon structures has resulted in two spinout companies, Microsaic and Nexeon, translating their research into products [B.2, B.3]. In addition to these commercial successes, this work has also contributed towards space exploration through its contributions to NASA's Phoenix Mars Mission [B.6].

Case study 3 in **low power electronics for healthcare** demonstrates impacts in saving lives in improving the health of patients [B.5], providing core technologies for large multinational companies (e.g. Life Technologies) [B.1 and B.2]. The work has also resulted in 2 spinout companies: DNA Electronics and Toumaz [B.3].

Case study 4 in **high-performance reconfigurable computing** demonstrates how our research has influenced the design flow of FPGA manufacturers such as Xilinx [B.1], used for financial risk modelling and reduction by J.P. Morgan and Scottish Windows, for geoscience and oil exploration by Chevron [B.1], and spinning out the start-up company Maxeler [B.2 and B.3].

Case study 5 in **power systems** demonstrates our impact in influencing the policies and strategies of governments, regulators and industrial practices [B.1, B.4]. This also resulted in a start-up company, Bboxx, which develops products for rural electrification [B.3 and B.5].