Institution: University College London (UCL)
Unit of Assessment: 12 Engineering

1. Unit context and structure, research and impact strategy

1.1. Structure

This *Engineering@UCL* submission covers research spanning a distinctively broad range of engineering disciplines, and encompasses a variety of departments, centres and institutes. Approximately 87% of the submitted staff are based in the UCL Faculty of Engineering Sciences (**FES**). **FES** is the largest of UCL's eleven faculties, and sits alongside the faculty of Mathematical and Physical Sciences and the Bartlett Faculty of the Built Environment within the School of the Built Environment, Engineering and Mathematical and Physical Sciences (**BEAMS**).

The six **FES** departments contributing to this submission are (staff FTEs in brackets):

- Biochemical Engineering (**BE**; 24.5)
- Chemical Engineering (**CE**; 29)
- Civil, Environmental and Geomatic Engineering (**CEGE**; 52.7)
- Electronic and Electrical Engineering (**EEE**; 41.7)
- Mechanical Engineering (**ME**; 38)
- Medical Physics and Biomedical Engineering (**MPBE**; 38.7)

This unit also includes engineers located with UCL's extensive biomedical research community in the Faculty of Medical Sciences (**FMS**):

- Research Department of Orthopaedics and Musculoskeletal Science (**OMS**), Division of Surgery & Interventional Science (12.8)
- Research Department of Surgical Biotechnology (**SB**), Division of Surgery & Interventional Science (5)
- Research Department of Targeted Intervention (**TI**), Division of Surgery & Interventional Science (2)
- Institute of Nuclear Medicine (**INM**), Division of Medicine (2)
- Centre for Medical Imaging (**CMI**), Division of Medicine (1)
- Centre for Precision Healthcare (**CPH**), Division of Medicine (1)

This underlines an institutional strategy that recognises that the most effective way for engineers to impact and transform healthcare is to embed them alongside clinical teams in hospital environments. We extend the same ethos to other application domains, enabling teams of engineers to work in close collaboration with end users (in areas such as communications, advanced propulsion, smart cities, manufacturing, energy, environmental remediation, and robotics) and at the UK's large facilities (section 4.2).

In addition, this submission includes staff based in the following cross-faculty facilities:

- London Centre for Nanotechnology (**LCN**; 6)
- Institute for Risk & Disaster Reduction (**IRDR**; 2)

This unit also hosts, or is a key partner in, a number of other cross-discipline thematic research centres and institutes, including the Institute of Healthcare Engineering (**IHE**), Electrochemical Innovation Laboratory (**EIL**), Institute of Communications and Connected Systems (**ICCS**), Centre for Medical Image Computing (**CMIC**), and Centre for Nature Inspired Engineering (**CNIE**). Figure 1 illustrates the relationship between this unit and the **FES**, UCL, and broader environment.

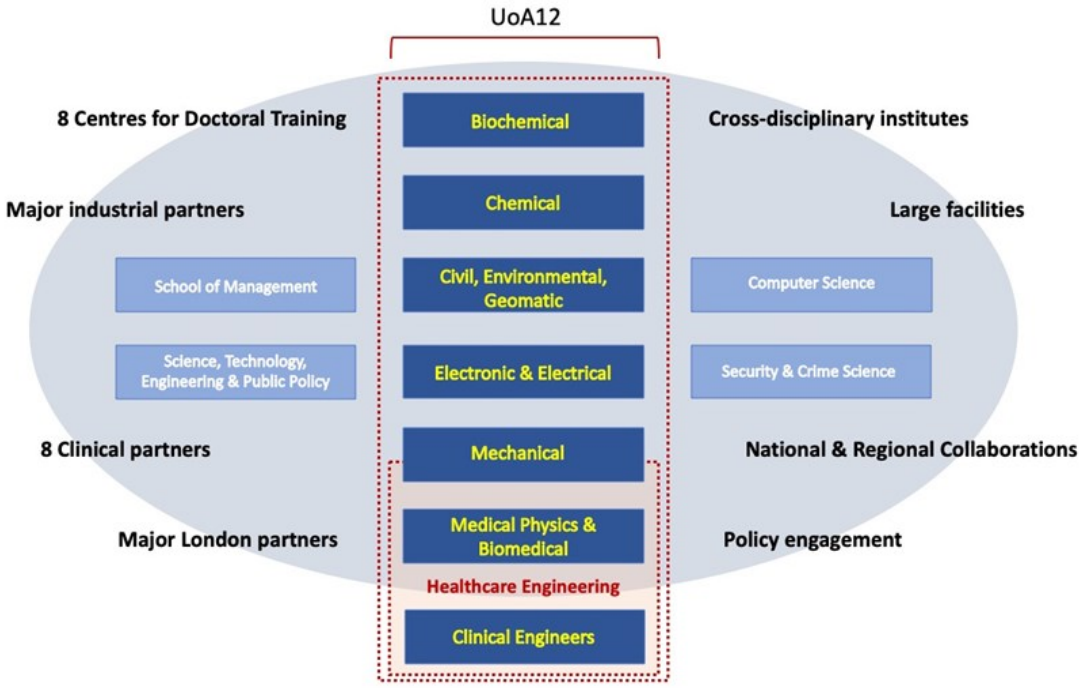

***Figure 1**: Engineering@UCL, showing the relationship between UoA12, UCL Faculty of Engineering Sciences (in grey), and its environment within and beyond UCL.*

The faculty's key strengths are its quality, global reach and influence, and its interdisciplinary and collegiate ethos. Collaboration across disciplines is fundamental to the philosophy of *Engineering@UCL* and is embedded into our strategy and working culture. We ensure porous boundaries between departments and institutes, to maximise impact and societal benefit. Staff are encouraged to work across these boundaries, to explore new research themes, and develop new partnerships within and beyond the faculty.

In keeping with UCL's characteristically interdisciplinary view of engineering, other **FES** departments are submitting to alternative UoAs: Computer Science (**CS**: UoA11), Science, Technology, Engineering and Public Policy (**STEaPP**: UoA20), Security and Crime Science (**SCS**: UoA20), and the UCL School of Management (**SoM**: UoA17). Many of the research themes covered in this submission involve close collaboration with researchers in these departments. For example, there is strong overlap between **EEE** and **CS** in areas of artificial intelligence (AI) and machine learning (ML); between **CEGE** and **STEaPP** via the multi-institution International Centre for Infrastructure Futures; between **EEE**, **CEGE**, **MPBE**, and **CS** on robotics; between **EEE** and **SCS** on aspects of forensic science; and between **CE** and **ME** in areas of energy and transport.

1.2. Research strategy

1.2.1. Strategy development

Research strategy for *Engineering@UCL* is founded on UCL's three core aims: 1) Nurturing research leadership; 2) Crossing boundaries between disciplines and communities; and 3) Realising public benefit.

The **FES** is led by Prof. Titchener-Hooker FREng, Executive Dean, who replaced Prof. Finkelstein CBE FREng in 2015 when he became Chief Scientific Advisor for National Security. The Dean sets the overall research and impact strategy in consultation with the Faculty Management Board, which includes twelve Vice Deans.

The Faculty's research strategy is developed within the framework of UCL's six Grand Challenges (*Global Health, Sustainable Cities, Cultural Understanding, Human Wellbeing, Justice & Equality*, and *Transformative Technology*). As well as contributing to all six themes, *Engineering@UCL* participates actively in all ten of UCL's Research Domains (Neuroscience; Personalised Medicine;

Populations & Lifelong Health; Cancer; Food, Metabolism & Society; Environment; eResearch; Microbiology; Collaborative Social Science, and Space), which are large, cross-disciplinary research communities that span UCL and partner organisations, fostering interaction and collaboration. They bring together a critical mass of expertise, and facilitate the breakdown of traditional barriers between disciplines which is fundamental to our research culture.

Within the broader framework, Heads of Department work with their respective departmental research committees, each chaired by a Research Director, to develop individual departmental strategies. The Vice Dean for Research (Prof. Kenyon) meets monthly with the Research Directors and with key senior staff from the Office for the Vice Provost (Research) to: a) facilitate the implementation of the Faculty's research strategy; b) coordinate large funding calls responses; c) ensure coherence in departmental research priorities and strategies; and d) address other key strategic research-related issues (including ethics, responsible research and innovation, ECR development, open access, and sustainable development). The **FES** Vice Dean for Health (Prof. Shipley) is also Director of the **IHE**, which serves to align healthcare engineering research strategy across multiple faculties (section 1.3.6). The **FES** Vice Dean for Strategic Projects (Prof. Lettieri) is also the Academic Director of **UCL East** (section 3.2.3), giving Engineering a key voice in future UCL-wide strategic initiatives. In 2020 **FES** appointed three Vice Deans for interdisciplinarity with complementary remits to address innovation, entrepreneurship, and policy.

In response to the launch of the Government's Industrial Strategy in 2017, UCL set up a School-based Industrial Strategy Alliance Forum, which meets monthly to review progress and identify opportunities. This reports to the termly **BEAMS** Research and Innovation Committee, chaired by the Vice Provost (Research) and attended by the Deans and Vice Deans of the three constituent faculties, along with key senior staff. Termly meetings between the Vice Provost for Research and the Vice Deans for Research from all eleven faculties ensure coherence of research strategies across UCL.

Our academic staff contribute to external strategy development through various mechanisms, including membership of national and international advisory boards, policy forums, and industrial liaison boards, and involvement with professional and learned societies. Examples include: Prof. Finkelstein (EPSRC Council, 2014-2017); Prof. Watson (President of the IET, 2017-2018; EPSRC Council, 2012-2015); Prof. Medda (EPSRC Strategic Advisory Network); Profs. Lye and Dalby (EPSRC *Manufacturing the Future* Strategic Advisory Team (SAT)); Prof. Kenyon (Chair of EPSRC *ICT* SAT; member of Executive Committee of European Materials Research Society); Prof. Spurgeon (EPSRC *Engineering* SAT); Prof. Miodownik (RCUK's *Public Engagement* SAT); Dr. Jervis and Prof. Lee (STFC Physical Sciences & Engineering Advisory Panel); Dr. Wang (EPSRC *Capital Equipment* SAT) and Prof. Titchener-Hooker (Rosalind Franklin Institute Trustee).

1.2.2. Strategic aims for research and impact

The principal strategic aim of **FES** is:

> *"To change the world for the better through world-leading engineering research, unconstrained by traditional disciplines, to produce real benefit to all sectors of global society in a sustainable and equitable manner."*

To achieve this we commit to:

- Support the discovery and development of transformative technologies;
- Exploit our strengths in cross-disciplinary research to expedite positive societal impact;
- Expand our entrepreneurial and innovation-based activities;
- Create and support the next generation of research leaders;
- Increase diversity of academic staff;
- Leverage our broad range of contacts to bring together focused communities of researchers, industry, users and policy makers to address new engineering challenges;
- Reach out to wider society to ensure maximum benefit and relevance of research outcomes.

As the research funding landscape continues to evolve, we also aim to:

- Inform and lead priority-setting for research funding;
- Define and address grand research challenges of the future.

To fulfil REF2014 strategic aims, our strategy has focussed on managing growth within key interdisciplinary research areas including quantum technology, bioengineering and healthcare, advanced materials, nature-inspired engineering, battery and propulsion technology, AI, the water-energy nexus, and communications. (Note that achievements are reviewed below by department/theme, since they were returned separately in 2014.) Although all researchers are affiliated with a department, centre, or both, frequent use is made of joint appointments to support interdisciplinarity.

Engagement with stakeholders is integral to our strategy, which include industry, funding agencies and policy makers, charities, public services including healthcare, and the general public. We encourage and support staff to take up positions on influential advisory boards, standards bodies, research funding agency boards, policy forums, etc.

Some of our major industrial partners (among >100 in total) are listed in table 1.

***Table 1**: Major industrial partners.*

3M	Costain	Huawei	NEC	Siemens
Airbus	DeepMind	IBM	Nikon	Sigma-Aldrich
Arm	Deutsche	Imec	Nokia	TfL
Arup	Telekom	Intel	Oclaro	Thales
AstraZeneca	Dow Corning	IQE	Pfizer	Thames Water
BAE Systems	Eli Lilly	JLR	Philips	Toshiba
BBC	Ericsson	Johnson	Plessey	UCB
BP	Ford	Matthey	Procter &	UK Power
BRE Group	Fujifilm	Laing O'Rourke	Gamble	Networks
Bruker	GE Healthcare	Lockheed Martin	Qinetiq	Verizon
BT	Google	Merck	Renishaw	Communications
Buro Happold	GSK	Microsoft	Roche	Vodaphone
CEA-LETI	Hitachi	Mitsubishi	Rolls-Royce	Xilinx
Cisco	Honda	National Grid	Samsung	Xtera

1.2.3. Strategic aims for enterprise

Engagement between UCL academics and industry is underpinned by two internal organisations: UCL Business (**UCLB**), a technology transfer company which supports and commercialises UCL's research and innovations; and UCL Consultants (**UCLC**) supporting academics undertaking consultancy.

The *Engineering@UCL* strategy for enterprise is founded on three main pillars of activity: Research Support, Innovation Programmes, and Entrepreneurship, steered by Industrial Advisory Boards at department and faculty level.

i) Research Support

We aim to make research impactful by leveraging key contacts in industry and government, and to make it financially viable and efficient in delivery. Researchers across **FES** work with over 800 companies, and relationships with industry are carefully fostered to ensure that UCL Engineering is widely recognised as the partner of choice. Engagements are stimulated internally and by our external partners, and are provided with appropriate contracting, financial and legal support, and access to project management resources. We aim to turn around all contracts within days, while keeping all engagements low risk. Many of our PhD studentships are supported by spin-out and start-up companies as well as by our larger industrial partners. (Section 3.1 provides more details on research income strategy and institutional support).

ii) Innovation Programmes

UCL has created and developed Innovation Programmes which link engineering with other disciplines or industry sectors. Examples include two Agritech programmes with Rothamsted Research, both receiving £3.5m VC investment:

- *Shake* (www.shakeclimate.org) – innovation hub for entrepreneurs and start-ups combating climate change in the areas of agriculture and food production, with science or tech-based ideas.

- *AgRIA* (www.rothamsted.ac.uk/agria) – translating innovations into commercial viability through rapid testing of ideas to solve agri-food problems.

Other established innovation programmes include:

- Lawtech (labs.uk.barclays/lawtech) – developed with the UCL Faculty of Law and Barclays Eagle Labs.
- EdTech (www.ucleducate.com/accelerator) – based on a completed 3-year project called EDUCATE with the UCL Institute of Education, jointly pursuing a sustainable worldwide innovation programme, and raising the first UK EdTech investment fund (currently £60M, reaching £120M by September 2021).

The UCL Electrochemical Innovation Lab (**EIL**, section 1.3.2) has a well-established EIL Incubator, which has led to spin-outs *Bramble Energy* and *Amalyst Ltd*. (developing advanced energy materials). This has now become a commercial venture, with the launch of *Prosemino Ltd*. to incubate innovations from the **EIL** in the area of electrochemical technology and power systems. This provides fast-track and agile progression of IP in critical areas for UK plc, including batteries (Batteries for Britain Government Initiative) and hydrogen (a pillar of the Government's Green Industrial Revolution). *Prosemino* provides a technology launch pad and a platform to train and guide academic researchers in translation.

iii) Entrepreneurship

FES provides staff and students a comprehensive set of entrepreneurship resources and support. We have a large peer community both within and beyond UCL who offer mentorship and access to services such as business support and pro-bono legal support.

UCL has created an 820m^2 innovation hub in Shoreditch: IDEALondon, home to some of the most ambitious and flourishing new businesses in London's Tech City. It is a partnership between UCL, EDF and Capital Enterprise, designed to give start-ups the space and support to grow. It was opened in 2013 by David Cameron and relaunched in 2016 when new partners joined. It has raised >£400M in venture funding for >85 resident companies, all of whom have links to UCL (UCL Founders, graduates employed, or active research engagements). Over 3000 jobs have been created. There is a thriving alumni community who carry out mentoring and support, and very active industrial partners who have included DC Thompson, Cisco, EDF Energy, and Barclays.

Recognising that the most fertile environment for starting companies was among our PhD student cohort, in 2016 we launched ConceptionX, which is a nine-month entrepreneurial programme to encourage our students to become Venture Scientists. So far we have supported over 100 PhD student teams, raised £8M in venture funds, and expanded the programme to cover 12 universities and 15 industrial sectors. ConceptionX has recently been invited to bid for a £5M award from the Research England Development Fund for a UK-wide rollout.

In 2018 UCL Engineering launched the Precision Medicine Accelerator in collaboration with UCL's Medical Faculties and UCL Hospital (UCLH). This programme has a £2M investment fund and offers a 6-month support programme with access to key decision makers, testbed and trial opportunities, support with regulatory pathways, and access to investment. Since its inception, >30 companies have gone through the programme, many of whom received significant private investment (£18M so far). Five companies gained classification of a Class 2 (or higher) medical device, with a further five currently being supported through the regulatory process. There have been many successful clinical trials, and some companies began scale-up activities. Partners of the programme include Nuffield Health, Cancer Research UK, and Roche.

1.3. Strategic aims: Achievements and future goals

Research achievements and future goals are reported below under headings corresponding to broad engineering themes. Much of the reported activity involves highly interdisciplinary research across multiple academic departments, centres, and institutes.

1.3.1. Biochemical Engineering

UCL hosts the UK's only academic department of Biochemical Engineering (**BE**), recognised globally as the discipline's founding laboratory, and for its pioneering studies that underpin processing of new drugs. Its strategy is to "*translate new discoveries in life sciences into novel products and processes for the benefit of human health and well-being*." The department is located within the Advanced Centre for Biochemical Engineering, which includes a £30M pilot scale bioprocessing facility, a Micro-Biochemical engineering and Lab-on-Chip facility, a Cell Therapy Bioprocessing Suite, and a Vaccines Manufacturing Suite. These facilities have been underpinned by £9.3M of capital investment (Gatsby, JIF, CIF, SRIF, RCIF, UCL) since 2007. Since 2014 the **BE** annual research expenditure grew from £3.8M to £6.8M.

BE research is strategically aligned with, and operates within, multiple collaborative networks, including the **IHE** (section 1.3.6), the Personalised Medicine Domain, and the BRC/Wellcome-funded Technology Innovation Networks (TINS), which link engineers, life scientists and clinicians at UCLH and Great Ormond Street Hospital (GOSH).

The research priority for **BE** in 2014 was to "*establish UCL as the international focus for research integrating advances in synthetic biology with future bioprocesing technologies in the chemical, (bio)pharmaceutical and cell therapy sectors*". Senior **BE** academics now direct several world-leading EPSRC-funded activities, including the £10M Future Targeted Healthcare Manufacturing Hub (Prof. Titchener-Hooker), the £7M Future Vaccines Manufacturing Research Hub (Prof. Micheletti), and a £10M EPSRC Centre for Doctoral Training in Bioprocess Leadership (Prof. Lye).

The Future Targeted Healthcare Manufacturing Hub is an internationally leading UK resource for bioprocess manufacturing research, with six spokes at Cambridge, Imperial, Loughborough, Manchester, Nottingham, and Warwick. The Hub leveraged an additional £11M from 42 industry partners, and engages National Catapult Centres, public health bodies, regulatory agencies, NHS, health charities, and government bodies, creating a major national asset. The grand-challenge-led research is precompetitive, and defined by consultation with end-users to ensure fundamental engineering innovations that strategically address critical industry challenges associated with manufacturing new advanced therapies emerging from clinical research. For example, the Hub has established the control and culture of cell therapies in stirred-tank reactors that have halved the processing time for personalised cell therapies pioneered and commercialised by UCL to eliminate cancers.

The £7M Future Vaccines Manufacturing Research Hub (VaxHub) is led jointly between UCL and Oxford as a UK resource for vaccine manufacturing and formulation research. VaxHub operates a hub and spoke model, including the University of Leeds, the London School of Hygiene and Tropical Medicine, Imperial College, and 17 industrial partners. VaxHub played a major role responding to the Covid-19 pandemic, providing a crucial network between Oxford originators of the ChAdOx vaccine, bioprocessing expertise at UCL, the BIA Vaccines Taskforce, and contract manufacturers Cobra and Oxford Biomedica.

BE has also established Centres of Excellence with AstraZeneca (since 2014) and Pall (since 2018), with investments so far exceeding £3.5M and £2.7M respectively.

Over the next five years, biochemical engineering research will focus on key national and international strategic areas, including enhancing rapid responses to scenarios such as pandemics, and enabling digital (Internet of Things, IoT) approaches in the responsive manufacturing of personalised healthcare. Another major growth area will be the development of net zero and sustainable biomanufacturing for renewable chemicals, materials and biopharmaceuticals, to transform these sectors into a circular economy. A key part of this strategy is aligned with the creation of a new Manufacturing Futures Lab at **UCL East** (section 3.2.3).

1.3.2. Chemical Engineering

Research in the department of Chemical Engineering (**CE**) is focused within five thematic groups (Catalysis & Reaction Engineering; Electrochemical Engineering; Molecular and Engineering Thermodynamics; Multiphase Systems, Process and Product Systems Engineering) and two UCL centres: the Electrochemical Innovation Laboratory (**EIL**) and the Centre for Nature Inspired Engineering (**CNIE**).

The **EIL** was formed as a cross-faculty facility in 2010 to accelerate impact, innovation, enterprise and research in electrochemical science and engineering. Its research spans fundamental science through to technology implementation: from atoms to devices. **EIL** houses over 80 researchers tackling key global challenges in electrochemistry, such as electrification of vehicles, global warming, and sustainable industry. Higher technology readiness levels (TRLs) are considered throughout the research process, ensuring that systems being studied are industrially relevant, and that any material discoveries have the potential to be scaled up to useful levels, even when the scientific programme of work is operating at the more fundamental, lower TRL. The **EIL** has £20.5M in current research funding, and hosts the UCL Centre for Correlative X-ray Microscopy and an EPSRC CDT in Fuel Cells and their Fuels. **EIL** is also the UCL arm of the National Centre for Grid Scale Energy Storage, and leads the STFC Global Challenge Network in Batteries and Electrochemical Energy Devices. The **EIL** has spearheaded UCL's involvement in the £78M Faraday Institution, and is part of eight of the Faraday's ten project consortia. **EIL** academics have led (e.g. EPSRC Roadmap for Tomography) and contributed to (e.g. "Foresight review of energy storage" for Lloyds Register Foundation) numerous white papers on energy and research policy, as well as served as expert witnesses for numerous investigations and litigations on battery failures (e.g. technical adviser to the Air Accident Investigation Branch). UCL has committed £8M and eight new academic posts to create **EIL**'s sister laboratory, the Advanced Propulsion Lab at **UCL East** (section 3.2.3).

"Establishing UCL as the UK focus for Nature Inspired Engineering" was **CE**'s major strategic goal in REF2014, and the **CNIE** launched in 2013 has subsequently achieved world-wide recognition for innovation. Research is uniquely focussed on uncovering fundamental mechanisms underlying desirable traits in natural systems, then applying those mechanisms to design and synthesise artificial systems that achieve the same traits. The Centre engages over 150 academics across UCL, the UK and beyond, as well as involving many industrial collaborations (>40 industries). **CNIE** was one of only two Frontier EPSRC manufacturing centres to obtain an EPSRC Progression grant to expand its target themes. It was instrumental in founding a UK Knowledge Transfer Network on Nature-Inspired Solutions (**KTN-NIS**) in 2019. The **KTN-NIS** took the **CNIE**'s definition for nature-inspired engineering as its basis, in a departure from narrow biomimicry, instead advocating fundamentally underpinned solutions that address industrial and societal challenges. **CNIE** has also impacted UCL's broader, interdisciplinary research strategy, with addition of the Grand Challenge for *Transformative Technology* (**GCTT**) in 2016. The **GCTT** focuses on responsible innovation, synergistically linking cross-UCL research, from engineering to the social sciences, to impact how innovation and technology can have far-reaching benefits for society and the planet.

During the assessment period, **CE** staff created three spin-out companies: *Bramble Energy*, which won the "Most Innovative Renewable Energy Solutions Provider" award at the 2019 Energy & Power Award; *Vesynta*, which won the 2019 Crick Start-up Award and received an NIHR Product Development Award; and the *London Advanced Materials Company*, which won the 2019 IChemE Business Start-up Award.

The goal for **CE** research over the coming REF period is to strengthen interdisciplinary, multiscale research on net zero and sustainable energy solutions and high value chemicals and functional materials manufacturing, underpinned by digitisation and data-driven engineering, nature inspired engineering and process intensification. Achieving these aims will benefit of extensive new facilities at **UCL East** (section 3.2.3), as well as targeted recruitment and new strategic partnerships.

1.3.3. Civil, Environmental and Geomatic Engineering

Our department of Civil, Environmental and Geomatic Engineering (**CEGE**) identified two research priorities in the REF0214 submission:

i) To be at the forefront of innovative reappraisal, study and implementation of new approaches to the disciplines of Civil, Environmental, and Geomatic Engineering.

ii) To implement new knowledge through engagement with governments at local, national and supranational level to encourage and facilitate political involvement in funding the implementation of the knowledge in world-changing applications.

To deliver these, there has been a substantial investment in new staff and facilities, and a harmonisation of departmental structure and organisation as a response to global changes. In

particular, we address the interconnected nature of twenty first century infrastructure and the impact of the fourth industrial revolution. The main research thrusts of **CEGE** run across three themes:

a) *Structures, infrastructure, risk and resilience*. **EPICentre** is the largest UK research centre for natural hazards engineering (21 academics and ~40 research staff and students). It is highly multi-disciplinary, involving collaborations across six UCL departments, from Statistics to Psychology. With >£10M research funding and >£400K in annual income from industry support and scholarships, **EPICentre** addresses the risk to society and infrastructure from earthquakes and other natural hazards, notably tsunamis. World-leading expertise in fire safety engineering has been added through the recent appointment of Prof. Torero, who served as an expert to the Grenfell Tower Fire Public Inquiry. The Structures Research Group (SRG) appointed four new academics and received a £2M investment in a new 300m^2 laboratory at **Here East** (section 3.2.2) which has a strong floor equipped with large rigs to enable high cycle fatigue testing and an environmentally-controlled facility to assess combined effects of extreme events, such as earthquakes, windstorms, and flooding. Staff were recruited at all levels to provide a sustainable staff profile, including Prof. Varga who founded the Infrastructure Systems Institute, aimed at influencing thinking toward complexity understanding of infrastructure systems. Strategic investments have enabled **CEGE** to approach both structural and infrastructural design, balancing sustainability and resilience in a holistic and practical manner. This distinctive approach builds on experience gained from hosting the interdisciplinary EPSRC funded £6.6M Urban Sustainability and Resilience doctoral training centre, and has resulted in **CEGE** hosting the £2.7m Coordination Node of UKCRIC (section 4.2).

b) *People-environment interactions*. UCL's Pedestrian Accessibility Movement Environment Laboratory (**PAMELA**) is a full-scale multisensorial environment for testing human interactions with their surroundings. **PAMELA** contributed to the design of a new person-centred underground system for London, and evaluation of the influence of gene replacement therapy on a patient's ability to interact with the environment. Research at **PAMELA** gave rise to the Global Disability Innovation Hub (now based in UCL **CS** department), which earned >£16M of funding, is operational in 61 countries, and has reached >4M people. **PAMELA** led to the creation of UCL's Person-Environment-Activity Research Laboratory (**PEARL**, section 3.2.4), which is supported by an investment of £48M (£9M EPSRC, £39M UCL) and six new academic appointments. **PEARL** provides the infrastructure to support research strategy for the next ten years, focussed on investigating how people interact with their environment at the scale of an entire railway station, high street, town square, or airplane. The vision for **PEARL** is to integrate its facilities with technologies and concepts developed by **CEGE**'s Healthy Infrastructure Research Group, which was founded in response to the spread of SARS COV-1.

c) *Information, transport and navigation infrastructure*. The Space Geodesy and Navigation Laboratory (SGNL) carried out core system engineering work with ESA on the Galileo navigation system, and worked with Google on advanced pedestrian and vehicle positioning algorithms based on large scale VRML city models. Its shadow-matching technology was implemented worldwide by Uber (in 65 countries). In collaboration with colleagues working on transport, SGNL will work on the emerging challenge of space traffic management resulting from the new space race and the rise of the satellite mega-constellation concept. Our Space-Time Lab (STL), which works on spatio-temporal data-mining of big data, collaborates extensively with the Metropolitan Police and Transport for London, and has recently won contracts related to the analysis of population movement and virus transmission. Its mission is to generate actionable insights from geo-located and time-stamped data for government, business and society.

1.3.4. Electronic and Electrical Engineering and Nanotechnology

The department of Electronic and Electrical Engineering (**EEE**) has strategic research focus on *Information*. Research topics include: information sensing (from nerve impulses to radar); information processing (from specialised analogue and digital signal processing to quantum information processing and neuromorphic systems); information transmission (coding, advanced wireless systems, optical communications, and networks); and information output (from nerve amplifiers to advanced display modelling).

The REF2014 strategic aims for **EEE** encompassed five themes:

- broadband access systems using fixed and wireless technologies;

- the creation of advanced interoperable networks;
- new information processing devices;
- silicon photonics;
- sensors of all types and their integration for security and healthcare applications.

Since 2014, long-term support for **EEE**'s five themes included an RCUK Basic Technology Programme and four EPSRC Programme Grants, with a total value of £18M. Key achievements and research strategies are outlined below.

a) An Institute of Communications and Connected Systems (**ICCS**) was established, with ~100 researchers across UCL. Research priorities for the next five years align with three strategic themes of the Institute:

- *Wireless communications* will explore development and exploitation of: spectrally efficient, multi-functional waveforms; beyond-5G system design; hardware-informed signal processing; and data-driven network design.
- *Future internet structures* will investigate network topology and control, and increase efficiency and resilience by implementing functions autonomically and creating a formal framework of descriptions of what networks must achieve.
- *Engineering of information processing* will focus on: information theoretic foundations of data science, AI and ML; merging intelligent sensing and processing; and cross-sector and industry-vertical challenges in visual and image processing.

Future research priorities include virtual reality systems and volumetric videos, defining signal processing and data-driven design for future technology. This research strongly engages with transport, healthcare, and the arts and culture sectors.

b) The Electronic Materials & Devices Group researches materials including inorganic semiconductors, oxides, two-dimensional layered materials, diamond, and metallic systems with spin-orbit interaction, in novel devices. Research is supported by two Programme Grants, two ERC grants, and multiple global academic and industrial collaborations. The group have established four start-up companies since 2017, and many members hold joint appointments with the **LCN** (section 3.2.1).

Research highlights include:

- Hybrid superconducting and cryogenic devices and a new platform (of major importance for Quantum Information applications) positioning single dopant atoms in precise locations in atomically thin layers to control their interactions.
- First observations of non-magnetic fractional conductance quantisation, with applications in Topological Quantum Computation.
- Understanding resistance switching in oxides, including observation of quantum transport. Resultant devices will enhance classical computation and develop neuromorphic concepts.
- Leading the £24M EPSRC UK Quantum Computing and Simulation Hub's silicon qubit workpackage, and participating in the €15 million European project "QLSI" - part of the EU Quantum Technology Flagship programme (>15 partners).
- New devices based on semiconducting diamond for sensor applications, including operation in nuclear reactors and measurement of brain activity.
- Modelling and fabrication of nanostructures for diverse applications including energy and biomedicine, self-adaptive surfaces for solar heat gain modulation, and probes for minimally invasive surgery.
- Semiconductor nanostructures and device concepts using metallic nanostructures which exhibit the relativistically-induced spin-orbit interaction. Magnon propagation and control of spins by a high frequency current injection have enabled us to become international leaders in the field of spintronics.
- Design and fabrication of heterostructures formed by combining different 2D materials and hybrid 2D/3D structures, for application in low-power electronics and (bio)sensing.

Future strategy is to build on the above achievements in which control over electronic processes has been accomplished through a combination of new knowledge and imagination, employing excellent facilities that a sustained record of grant funding success has enabled the group to develop.

c) UCL's Optical Networks Group focuses on communications system technologies, operating at all time and length scales. Our strategic aim over the assessment period was to increase the transmission capacities of optical channels and networks by two orders of magnitude, which was achieved with the support of a £4.9M EPSRC Programme Grant, "Unlocking the capacity of optical communications". A variety of new techniques to enhance communication in the nonlinear regime were demonstrated.

Future strategy is encapsulated in a £6.1M EPSRC Programme Grant, "Transforming networks - building an intelligent optical infrastructure", which began in 2018. Its goal is to transform the design of the optical networks that form the global digital communications infrastructure, and introduce ML-enabled intelligence into all levels of dynamic, nonlinear optical communications network infrastructure.

A recent success is the development of our experimental test-bed facility, used extensively in collaboration with industry partners to demonstrate the generation, transmission and processing of advanced modulation formats, including multiple data transmission records widely reported in the media: 120Tbit/s over 600km, 74Tbit/s over 6000km, and 178Tbit/s using over 16THz of optical fibre bandwidth. Expansion of our experimental capabilities is a pillar of future strategy, and is supported by a recent £900K EPSRC Strategic Equipment Grant.

d) The REF2014 strategic aims for the **EEE** Photonics Group were to:

- build on the integration of lasers on Si to create integrated circuits combining CMOS electronics with Group III-V photonics;
- demonstrate the first ultra-high capacity (>10Gb/s) THz wireless systems, and apply coherent techniques to quantum state manipulation and information processing;
- explore new network designs to support the future internet;
- expand work on energy related technology.

The first aim was achieved by extending our Molecular Beam Epitaxy (MBE) clean room, installing a new SiGe MBE growth system with UHV interconnect to a Group III-V system. This enabled the first demonstration of practical semiconductor lasers on CMOS compatible substrates, and funding for the UK Future Compound Semiconductor Manufacturing Hub (with Cardiff, Manchester, and Sheffield) and the EPSRC National Epitaxy Facility (with Sheffield and Cambridge). We also lead a new £6.1M EPSRC Programme Grant (with Cambridge, Cardiff and Southampton), integrating quantum dot devices with silicon photonics.

Achieving the second aim led to a £6.5M EPSRC Programme Grant with Leeds and Cambridge Universities, and the first demonstration of photonic injection locked quantum cascade lasers. Our achievement of the third aim led to the award of the £5M EPSRC National Dark Fibre Facility and a £1.4M EPSRC-funded collaboration on converged optical and wireless networks, while we advanced the fourth aim by joining with the University of Cambridge to establish a new EPSRC CDT in Connected Electronic and Photonic Systems.

Our future strategy involves developing new integration platforms based on III-V semiconductor structures, on native substrates and on silicon, and new applications. We will also focus on THz and photonic wireless links, investigating uses for: i) bridging between processors in data centres; ii) in-building delivery of ultra-high-speed wireless services; and iii) intra-satellite RF - THz signal distribution and processing and high data-rate inter-satellite links. Dark fibre research will incorporate wavelength routed switches and bridges into Layer 2 networks. In collaboration with the **ICCS** we will focus on information transmission and processing across nanometric to megametric scales, with emphasis on plasmonic devices, classical and quantum meta-materials, interconnects, and wireless systems. Meta-materials research will involve: i) expanding the emerging field of topological photonics in the area of non-linear optics, enabling active photonic nanodevices with new functionalities; and ii) smart software development for photonic systems design, incorporating ML. Finally, we will explore applications such as 3D LIDAR, where we have patented 3D object recognition and modelling (exploited by spin-out *Correvate Ltd*.).

e) The REF2014 strategic aims and subsequent achievements of our Sensors Systems & Circuits group were as follows:

- *Build on geophysical radar work*. Research was applied to avalanche imaging and Antarctic ice shelf imaging (with the Swiss SLF institute and BAS), to explore the influence of ocean circulation on ice shelf melt rate (impacting global sea levels), and extended this work to investigate pyroclastic flows.
- *Further develop biomedical sensing*. Achievements include the Continuous Regional Analysis Device, a diagnostic monitoring technology based on electrical impedance tomography, evaluated on 200 patients in four hospitals.
- *Develop new smart antenna and radar technologies*. New industrial collaborative projects have been developed (e.g. Cisco, Qinetiq, Vodafone, Huawei), including new applications in areas of Agritech and IoT and applications in developing countries.

We added control to our portfolio in response to a UCL strategy prioritising control and systems as a fundamental science. Successes include the development of fundamental nonlinear and estimation control paradigms applicable both to complex systems and distributed fault tolerant control strategies. We have applied this work to the understanding of control mechanisms in biological systems and to classical engineering problems in collaboration with the automotive industry.

Our strategic priorities are:

- *Antennas*: we will develop new generations of radar systems, including those inspired by dolphins, capable of discrimination between linear and nonlinear scatterers. We will explore wideband antennas and reconfigurability to design antennas for different applications, including long range, low power IoT, smart home/city and wearables.
- *Radar*: our aim is to be world leading in multistatic radar sensing and geophysical imaging using RF sensors. We will research multistatic clutter and target phenomenology via collaboration with industry (Leonardo MW, BAE Systems and Thales) and build on successes in passive through-wall radar imaging and extend geophysical imaging.
- *Bioelectronics*: we will collaborate with clinical colleagues on biomedical technologies incorporating advanced microelectronics design for vital signs monitoring, drug delivery, cancer detection etc. Goals include bioelectronic medicines for heart transplantation, and wearable technologies incorporating printed electronics for neonatal monitoring.
- *Control*: work will focus on development of verifiable control and monitoring systems to ensure safe operation of uncertain autonomous systems. We will continue as key partners in the UCL Robotics Institute at **Here East** (section 3.2.2). We will apply our extensive expertise in robust control and monitoring for large scale distributed systems to achieve efficiency, reliability and both cyber and physical security for an increasingly connected world.

1.3.5. Mechanical Engineering

For our department of Mechanical Engineering (**ME**), the previous aims, achievements, and future goals of research in three core areas of the discipline are described below. A fourth is covered under healthcare engineering (section 1.3.6).

a) *Materials, Structures and Manufacturing* was established as a new theme in 2018 in response to strategic analysis that showed that new materials and manufacturing technologies were key to achieving the UK's targets for both net zero and industrial growth. Existing expertise at UCL was supplemented with six new academic appointments and supported by a £3M investment in infrastructure (funded by EPSRC, RAEng, and UCL). Activity has grown rapidly with the establishment of the Plastic Waste Innovation Hub and a lab with 20 researchers at Harwell Campus working with Diamond Light Source, the Central Laser Facility and ISIS Neutron Source. Strong links with UK manufacturing have been developed, including involvement in the EPSRC Future Manufacturing Hub "Manufacture using Advanced Powder Processes", resulting in £14M in grants from UKRI, H2020 and industry (e.g. Rolls-Royce, Renishaw). Future strategy is focused on a £15M investment to establish a Manufacturing Futures Lab at **UCL East** (section 3.2.3), which will enable a focus on ML, digitisation, micro/nanotechnology and additive manufacturing technologies.

UCL's Institute of Making, established in 2013, provides prototyping and making facilities and is internationally known as an interdisciplinary materials research hub. It has supported >6000 projects across UCL and has fostered several spin-out companies including HEXR, developing 3D-printed bike helmets. A further £5M investment will expand this activity at **UCL East**.

b) *Marine Research*. A primary REF2014 aim was a focus on "engineering in extreme marine environments". This led to research using world-leading full-scale test facilities at KOSORI (Korea) on extreme temperature performance of structures, in collaboration with major Asian ship and offshore structure builders, and technical leadership of an EU H2020 project which resulted in an Arctic Voyage Planning Tool undergoing commercialisation. Meanwhile, research has been conducted on ship-wave-ice interactions as part of a joint research centre on deep water challenges (Lloyd's Register Foundation) with partners Shanghai Jiaotong University, Harbin Engineering University, and the Chinese National Science Foundation. MoD funding has underpinned research on the world's first ocean-going trimaran ships, and support from BMT Group (including a BMT Chair of Maritime Engineering) has enabled new research on ship design. The next five years will focus on autonomous shipping, including surface and subsea vehicle design, and assuring long-term autonomy of underwater vehicles in collaboration with the National Oceanographic Centre.

c) *Energy and the Environment*. Previous strategy focused on three areas:

- *Clean engines and fuels*: work has been conducted on development of ultra-efficient engines, low-emission gas turbines, hydrogen propulsion for space, and biofuels modified to reduce soot. This work involved collaborations with BP, Cella Energy, Delphi, Geely Auto, JLR, PHE, Reaction Engines, Ricardo, and Siemens.
- *Complex fluids and multiscale multiphysics*: research supported by EPSRC and industry (GSK, Xaar, CPI, Khuner AG, Pall Biotech, iBET) yielded improved energy harvesting and mixing applications, novel microfluidic technologies to harness waste heat energy, and advanced engineering tools for improved scaling up/down strategies for bioreactors.
- *Modelling, simulation and design*: UCL leads the UK Consortium on Mesoscale Engineering Sciences involving 31 international organisations with £40M leveraged from UK/EU funders and industry. Capability has been developed for modelling and simulation across atomic/micro-/meso-/macroscales, 3D inverse design, and multi-objective/multi-disciplinary optimization, contributing to both open-source and commercial codes which are implemented worldwide.

Future research will exploit a £50M institutional investment in the Advanced Propulsion Laboratory at **UCL East** (section 3.2.3) to accelerate decarbonisation of the energy sector through advanced hydrogen technologies, energy storage, electric and hybrid propulsion (joint with **CE**). In addition, advanced mesoscale and multiscale simulation tools will be developed as low-cost and sustainable alternatives to physical prototyping and testing as part of UKRI's £46M ExCALIBUR programme.

1.3.6. Healthcare Engineering

The Institute of Healthcare Engineering (**IHE**) was launched in 2016 to bring together UCL's extensive research activity in engineering applied to healthcare, distributed across multiple faculties, departments, institutes, and centres. The **IHE** research strategy is to exploit UCL's unique platform for cross-disciplinary research to develop and translate innovative engineering solutions to unmet clinical needs. Our healthcare engineering research covers all stages of the translational pathway, from recognising needs, identifying opportunities in foundational sciences, to the development of technologies for use in hospitals.

The **IHE** facilitates connections between our engineers and experts in diverse areas (e.g. medicine, computing, data sciences, biosciences, ethics, etc.) and with clinical partners in primary and secondary care (e.g. UCL-affiliated Biomedical Research Centres at UCLH, Moorfields, and GOSH). Mechanisms to stimulate cross-disciplinary collaborations include regular workshops focussed on priority research areas (>20 so far), and the IHE-Rosetrees Trust Healthcare Engineering Awards (£400K invested so far), established to support new projects with high translational potential.

IHE facilitated a £4M NIHR UCL-UCLH Biomedical Research Centre cross-cutting theme in Healthcare Engineering & Imaging which supports innovations in the technical and computational aspects of diagnostic imaging and image-guided surgery. **IHE** also works closely with other bodies

to accelerate the translational pathway including leading the Translational Research Office's Therapeutic Innovation Network (TIN) on Devices & Diagnostics.

A recent example of an **IHE**-led high-impact project is the establishment of *UCL Ventura:* our engineers and clinicians collaborated with Mercedes AMG High Performance Powertrains to create a Continuous Positive Airway Pressure (CPAP) device that could be rapidly manufactured and delivered to NHS hospitals ahead of the April 2020 surge in Covid-19 hospital admissions. The Ventura CPAP is now used in over 150 NHS hospitals with over 10,000 produced in three months to help patients in over 15 countries.

IHE has led the development of CHIMERA (Collaborative Healthcare Innovation through Mathematics, Engineering and AI), a £2.6M EPSRC-funded centre launched in 2020. CHIMERA uses tools such as machine learning to analyse anonymised data from 40,000 intensive care patients at UCLH and GOSH, to gain new understanding of how patient physiology changes to improve clinical decision-making.

Our Medical Physics & Biomedical Engineering (**MPBE**) department maintains a strong focus on clinical translation, with virtually all research involving clinical and/or industrial collaborators. **MPBE** has increased in size from 16 reported staff for REF2014 to 40 in 2021 as a result of awards to fund the establishment of new Programmes and Centres (outlined below), and an exceptional record of achieving externally-funded early-career fellowships (averaging two per year since 2014). **MPBE** has eleven reported staff currently supported on five-year fellowships (Royal Society, EPSRC, RAEng, etc.), and has three additional reported staff who completed such fellowships since 2014. **MPBE** co-hosts the Centre for Medical Image Computing **(CMIC),** which currently includes 22 affiliated academic staff across multiple engineering and clinical science departments, and maintains a £30M grant portfolio including £5M in industry contracts.

In the REF2014 submission, **MPBE** identified four priority research areas. The achievement of strategic aims for research and impact are outlined below.

i) *Interventional devices***.** In 2016, UCL was awarded £13.5M to establish the Wellcome Trust/EPSRC Centre for Interventional and Surgical Sciences (**WEISS**). The Centre, which impacts research across multiple units of assessment, enables engineers to work alongside clinicians in a purpose-built facility (Charles Bell House) to deliver innovative interventions which translate to the hospital. **WEISS** has leveraged multiple other grant awards, covering research topics such as image guided liver surgery, endoscopic screening, and peritoneal laparoscopy - it is on target to generate £65M of external funding during the first five years. New commercial links with industry have been established (e.g. Philips, Elekta, etc.) and three spin-out companies have been launched to translate innovations into clinical practice (Smart Target, Odin Vision, and Echopoint Medical).

ii) *Contrast agents and biomarkers***.** UCL's development of magnetic nanoparticles for biomedical applications led to the introduction of the world's first licensed nanoparticulate injectable medical device, the Sienna+ tracer, and its detection system, the SentiMag. An improved formulation with optimised lymphatic transport characteristics, called Magtrace, was developed in 2015. A UCL spinout company, Endomagnetics Ltd., has introduced this new technology which uses magnetic materials to locate the sentinel lymph nodes that are key indicators of cancer metastasis. As well as improving patient outcomes, the system considerably improves hospital efficiency since, unlike radioisotopes, the magnetic tracer requires no special handling.

iii) *Ultrasound***.** A biomedical ultrasound group (BUG) was launched, generating £6.9M in grant income since 2014. BUG is conducting the first human trials of technology for targeted therapeutic ultrasound modulation of the adult deep brain, and worldwide impact has been achieved through development of the k-Wave software package for modelling of acoustic fields, which now has >10,000 users in 70 countries.

iv) *Proton Therapy***.** Research capacity has been built up in advance of opening the £130M UCLH Proton Beam Therapy Centre to patients in 2021, including three new academic appointments, supported by a CRUK Radiation Oncology Research Unit (RadNet) grant in 2019 with an initial 5-year investment of £14M. An additional £2M charity donation has been provided to support translational research.

MPBE will continue to maintain its research programmes in radiation physics, ultrasound, biomedical optics, implanted devices and assistive technology, magnetic resonance imaging, medical image computing, and electrical impedance imaging. Strategically important priority areas for future development are as follows:

i) *Interventional & surgical sciences***.** Future investments will prioritise **WEISS** to become an international leading centre. Impact will be achieved through clinical translation (e.g. MRI-guided HIFU and sonodynamic therapy for minimally invasive treatment of prostate cancer and nephron sparing kidney treatment), industrial partnerships, and creation of spin outs. **WEISS** will nurture translation through pump priming to develop proofs of concepts. We will focus on new multidisciplinary collaborations, such as combining expertise in materials science and optics to create novel fibre-optic sensors for *in vivo* imaging. **WEISS** provides a framework and support for regulatory activities and clinical studies, greatly accelerating pathways to impact. **WEISS** is co-located with UCL's Research Department of Targeted Intervention (**TI**), whose teams of clinicians and scientists will focus on minimally invasive technologies, tissue engineered tissue/disease models, and biomarkers of risk.

ii) *Phase contrast x-ray imaging***.** Having pioneered the field of phase contrast x-ray imaging at UCL, emphasis is now on fulfilling the technology's commercial potential. An intra-operative specimen imaging scanner built jointly by UCL and Nikon will be clinically evaluated with the aim of reducing repeated operations in breast conservation surgery. Another prototype scanner, aimed at detecting concealed explosives, will be tested at the Cranfield Ordnance Test and Evaluation Centre, supported by the launch of a start-up, *XPCI Technology Ltd*. A recent £5M EPSRC Prosperity Partnership award with Nikon will apply the imaging technology to new areas such as industrial inspection and manufacturing. This activity will be based in a new **FES**-funded centre, alongside UCL's division of the EPSRC £10M NRF for Tomography.

iii) *Photoacoustic imaging***.** The **MPBE**'s photoacoustic imaging group will pursue translation of its many innovations. A spin-out DeepColor has recently been launched to commercially exploit a new Fabry-Perot sensor technology pioneered at UCL, initially as a tool for guiding reconstructive surgery and in the longer term for the diagnosis and treatment-monitoring of cancer and cardiovascular disease. Other research objectives include: the development of a practical photoacoustic scanner based on a microresonator array; development of a compact MEMS based hand-held probe for real-time imaging; and demonstration of an endoscopic 3D photoacoustic imaging probe *in vivo*.

iv) *Proton and advanced radiotherapy***.** This research will exploit the world-leading facilities at the new UCLH Proton Beam Therapy Centre, with a mission to improve survival and quality of life for cancer patients. Key goals are to increase efficacy of radiation therapies whilst reducing toxicity to healthy tissue, and tackle radiation resistance which leads to tumour recurrence.

Our research on biomechanical engineering is largely based within the **ME** department. The REF2014 priority areas for this activity were to expand and strengthen research on biomedical ultrasound, cardiovascular devices and microcapsule drug delivery, and to launch new research on biomedical computational modelling. Major achievements during this period include:

- creation of an open-source ultrasound therapy optimisation platform (OptimUS);
- invention of the UCL Triskele heart valve, undergoing preclinical investigation;
- a spin-out *AtoCap Ltd*., marketing new microencapsulation technology for drug delivery;
- a new international consortium translating computational modelling into clinical science;
- the *UCL Ventura* CPAP device in response to Covid-19 (described above) commissioned by the DoHSC and developed in the **ME** design and manufacturing facility, MechSpace.

The biomechanical engineering group has hosted several multi-institutional strategic awards and served as a hub in research networks (e.g. CHIMERA, ThUNDDAR, and ImagingBioPro). Translation of new technologies has been achieved through close collaboration with local hospitals (UCLH, GOSH, Moorfields and their NIHR Biomedical Research Centres), research institutes (e.g. Francis Crick Institute), charities, and medical research organisations. Future strategic development will involve investment in existing core capabilities. Tissue engineering and cardiovascular

theranostics will be the target application areas, to build a pathway from an understanding of fundamental mechanobiology to commercial impact through spinouts and clinical translation.

The Research Department of Orthopaedics and Musculoskeletal Science (**OMS**) is a translational research centre where engineers and clinicians pursue research into restoration of pain-free functional mobility and independent living. It is located on the Royal National Orthopaedic Hospital (RNOH) site in Stanmore, with some staff located at the Royal Free Hospital (RFH) in Hampstead and at the main UCL site in Bloomsbury. Research is focussed on new approaches for rehabilitation and implant science that includes robotics, neuromodulation, biomechanics, neuro-prosthetics, tissue engineering, and intelligent artificial joints. **OMS** identified the following research priorities in the REF0214 submission:

i) *Orthopaedic implants*. A team led by orthopaedic surgeon Prof. Hart collected over 10,000 failed spine, hip and knee implants removed from patients in 29 countries, with corresponding imaging and clinical data, and identified mechanisms and risk factors for failure. Outcomes enabled the European Scientific Committee on Health and Environmental Risks to update their implant safety recommendations, and led to Medicines and Healthcare products Regulatory Agency (MHRA) recommendations against the use of modular neck implants because of risks of severe corrosion. The same team discovered that metal-on-polyethylene (MOP) hip implants do not experience the wear and corrosion associated with metal-on-metal implants. This informed British Hip Society advice to surgeons about management of MOP patients, and led to the avoidance of unnecessary tests and procedures (with NHS savings of £9M).

ii) *Cell and tissue engineering*. **OMS** established the first international consortium for the Bioprinting Research Platform in 2019. Dr. Kalaskar contributed policy documents on 3D bioprinting in medicine commissioned by the UK Parliamentary Office of Science and Technology (POST), and to an international study on 3D printing technology for the UK Patent Office.

iii) *Disability Science*. A £2.3M investment, matched by the Aspire Charity, established the Aspire Centre for Rehabilitation Engineering and Assistive Technology (**CREATe**) in 2014. The Centre has developed novel treatments based on virtual reality and robotics targeting neuropathic pain in amputation, nerve injury and spasticity in spinal cord injury. This resulted in two first-in-human clinical trials at the RNOH and the world's first 3D printed bionic hand for pain management (with NHS savings exceeding £500K).

iv) *Musculoskeletal disease*. **OMS** developed a novel osteochondral scaffold therapy for the early surgical intervention of osteoarthritis, for which Arthritis Research UK funded a first-in-human clinical study at RNOH. Work at **OMS** has also led to a first-in-human clinical trial of a device for patients with severe neck muscle loss and unable to lift their head. Results led to funding to develop neck collars for motor neuron disease patients, and EPSRC early commercialization funding to set up clinical trials. The prototype was nominated for the 2020 Design prize at London Design Museum.

In the next assessment period, the strategic priorities for **OMS** are to:

- Identify and target key engineering challenges in orthopaedics and enable pathways to clinical impact for new technologies;
- Develop new orthopaedic interventions and fast track their integration into the NHS;
- Revolutionise musculoskeletal rehabilitation by incorporating state-of-the-art technology-driven diagnostics and treatment monitoring.

The Research Department of Surgical Biotechnology (**SB**), based at the RFH, is home to engineering and clinical expertise in biomaterials, tissue engineering, transplantation, vascular and reconstructive surgery, nanomedicine and solid cancer theranostics. Its mission is to drive uptake of innovative treatments and improve surgical practice.

Major engineering achievements since 2014 include the first-in-human use of an EPSRC-funded 3D printed laryngeal stent. In collaboration with surgeons at GOSH, **SB** engineers developed the stent as a short-term implant for paediatric laryngotracheal reconstruction. Meanwhile, **SB** collaborated with *Nanoco Technologies* to develop indium-based quantum dot nanoparticles as a luminescent probe for preclinical imaging.

In 2020, an Engineering Hub was established at the RFH as an "incubator" for surgical and engineering groups collaborating through **WEISS** on projects related to hepatic, pancreatic & biliary surgery and transplants, and vascular surgery. Meanwhile, UCL, the Royal Free Charity, and the Pears Foundation have jointly invested £47M to create the Institute of Immunity & Transplantation (**ITT**) at the RFH campus. Strategic development of healthcare engineering at the **ITT** will include:

- development of basic science platforms for transplant surgery, including innovations in machine perfusion technology;
- tissue engineering and cell therapies for tissue repair and reconstruction, applied to liver, kidney, pancreas, bile duct and lymphatic tissue;
- nanomedicine and targeted drug delivery systems for non-viral gene therapy and immune-therapy;
- organ-on-a-chip techniques to provide 3D *in vitro* models of liver, kidney, and pancreas for investigating biological function and pathophysiology, immune systems, cell therapy and drug discovery.

The UCL Institute of Nuclear Medicine (**INM**) is the only UK academic department of nuclear medicine; its engineers engage in clinically-focused projects, including PET/CT applied to lung imaging and development of the world's first clinical SPECT/MRI system. Industry collaborations include motion estimation in PET/CT imaging (with GE); methodological aspects of PET/MRI (Siemens); and low-dose molecular breast imaging (Kromek).

The UCL Centre for Medical Imaging (**CMI**) is focussed on translation of innovations in medical imaging, from conducting first-in-human interventions to multi-centre NHS trials. Recent achievements include:

- development of MRI luminal water imaging for prostate cancer, now expanding from single-centre to multi-centre trials;
- contribution towards establishing the UK's first NHS-approved service for treating spina bifida *in utero*.

CMI objectives for the next five years include development of new gastro-intestinal MRI analysis techniques and the establishment of clinical trials, in collaboration with other HEIs (Nottingham University, QMUL) and with *Motilent Ltd*.

UCL's Centre for Precision Healthcare (**CPH**) conducts engineering research in regenerative medicine, surgical intervention, and drug delivery. Achievements during the period of assessment have led to a portfolio of patent applications, licencing agreements with various industry partners (e.g. *AGA Nanotech*), formation of a spin-out (*Luna Therapeutics*), and development of UCL's first MHRA-approved biomaterial for tissue regeneration. **CPH** has also been responsible for first-in-human clinical studies to evaluate safety and efficacy of Class III medical devices for treatment of fistulas, and development of advanced therapeutic products and drug-device combinations for treatment of incontinence, blindness, cardiovascular disease and adjuvant cancer therapy.

1.3.7. Risk & Disaster Reduction

The cross-faculty Institute for Risk and Disaster Reduction (**IRDR**) studies global risks and means of reducing disasters. Examples of impact during the assessment period include:

- contributions to global preparedness for wide-area power failures, including a study featured on UN website *Preventionweb*, highlighted by the US National Library of Medicine as a key document supporting wildfire response and recovery in California.
- contributions to closed-door workshops on power failures promoted by London Resilience and by Public Health England;
- collaboration with London's public sector decision makers on anticipating the cascading effects of satellite failures;
- development of a decision-making support tool for the UN Office for Disaster Risk Reduction.

IRDR will continue to grow its leadership in this discipline, and will contribute to the 2022 UN Global Assessment Report on Disaster Risk Reduction.

1.4. Research transparency and integrity

UCL is fully committed to open access to scientific information. As part of its Academic Career Framework, UCL requires all research outputs to be available through Open Access wherever possible, and **FES** aims to achieve 100% of published manuscripts deposited in an open access repository within 3 months of acceptance (currently 81%). UCL's Research Software Development Group (section 3.3) provides training and support on distributing open-source code through *GitHub*, and UCL provides a Research Data Repository to openly publish all research data.

All *Engineering@UCL* research operates under a Code of Conduct for Research, which commits UCL to maintaining the integrity and probity of academic research. All researchers are required to abide by the Code, the General Code of Ethical Principles, and the Principle of Integrity set out in the UCL Statement on Research Integrity. UCL has been a leader in the development of research integrity policy, and in 2014 was selected as home of the UK's National Hub for Responsible Research and Innovation (RRI), which brought together researchers, policymakers, industry and the public, as part of a €7M project funded by the European Commission.

Many key RRI concepts now adopted by research councils are being developed by UCL's Department of Science & Technology Studies (**STS**). **FES** has worked closely with **STS** to develop online training modules aimed initially at doctoral students, by providing instructional design, pedagogy expertise, and project management. For example, a level 1 course provides an understanding of RRI in the four key areas identified by EPSRC's AREA Framework for Responsible Innovation: Anticipation, Reflection, Engagement, and Action. Online modules and workshops cover the history of RRI, ethics, open science, gender and diversity, public engagement, and responsiveness. Higher level courses provide students with opportunities to: design and conduct ethical research aligned with social needs; improve creative and critical thinking; enhance innovation capacities; and improve funding application skills. This programme was rolled out in 2019 with an initial cohort of 20 doctoral students. Engineering doctoral students also receive training in research integrity through our Cumberland Lodge retreats (section 2.2.3), with workshops that focus on case studies of research fabrication, plagiarism, and other topics.

Future plans include commercialisation of the RRI programme in partnership with **STS** to offer modules to other academic institutions, industry, public funding bodies, and the public. We are also working with the Royal Academy of Engineering (RAEng) Leaders programme to train the next generation of research leaders.

Through their research committees, individual engineering departments are responsible for developing and promoting strategies for maintaining excellent standards of research integrity, and for providing mechanisms for confidential reporting should breaches of integrity be suspected.

As a signatory of the San Francisco Declaration of Research Assessment (DORA), UCL has openly rejected the use of quantitative metrics commonly associated with journal impact factors as a measure of research quality.

2. People

2.1. Staffing strategy and recruitment

To support our strategic goals, we have increased academic staff from 183.96 to 256.18 FTEs since 2014 - attracting the best engineers from the global talent pool. To ensure transparency in recruitment all posts are advertised nationally and internationally and in parallel we proactively approach individuals we identify as high-calibre candidates with invitations to apply. We particularly seek out candidates who are female and from other under-represented groups, in accordance with our commitment to increase diversity.

A significant number of academic staff have been appointed to permanent positions following prestigious, long-term (e.g. 5-year) fellowships held at UCL, in recognition that such fellows represent the cream of research talent. As a commitment to their career development we encourage and support our best postdoctoral researchers to apply for external fellowship schemes. As

testimony to the success of this strategy, we currently hold more RAEng Research Fellowships than any other institution (11 awarded since 2014).

Competitive fellowships awarded to this unit since 2014 are listed below. We highlight in particular that four of our senior academics have received RAEng Chairs in Emerging Technologies: prestigious 10-year awards providing the opportunity to focus on development of disruptive technologies.

Table 2: Competitive Fellowships awarded to Engineering@UCL since 2014.

Fellowship scheme	Recipients
RAEng Chair in Emerging Technologies	*Lee, Olivo, Shearing, Stoyanov*
RAEng Research Chair	*Griffiths, Robson*
RAEng Senior Research Fellowship	*Parikh*
RAEng Research Fellowship	*Bosi, Chen, Colchester, Endrizzi, Galdino, Hagen, Lavery, Materazzi, Mehonic, Powell, Veiga*
UKRI Future Leaders Fellowship	*Collins-Fekete, Ferreira, Hales, Kumar, Martin, Palombo, Talibi*
EPSRC Early Career Fellowship	*Cooper, Hellier, Psaras, Treeby, Zervas*
ERC Starting Grant	*Iglesias-Gonzales. Papakonstantinou, Tiwari*
ERC Consolidator Grant	*Morton, Panoiu*
UKRI Innovation Fellowship	*Balakier, Collen, Liu, Noimark*
Wellcome Trust Senior Research Fellowship	*Tachtsidis*

Towards the end of their fellowships, early career fellows are invited to undergo a formal process to recruit them to proleptic academic appointments. For example, in **MPBE** eight former fellowship holders are among its HEFCE-funded academic staff (seven are professors), and in **EEE** all four RAEng Research Fellows hold proleptic lectureships.

Engineering@UCL has recruited internationally excellent people at all career stages, with strong growth in selected areas to support REF2014 strategy. Examples include:

- **EEE** (including LCN) expanded from 38 to 46.7 FTEs, recruiting from leading national and international centres, including Dr. Lombardo (Cambridge), Dr. Ritchie (DSTL), Dr. Toni (EPFL).
- **MPBE** made thirteen (8 lecturer, 5 professorial) appointments in targeted areas of healthcare engineering, including two professors and a lecturer to underpin new research in proton and advanced radiotherapy.
- **BE** appointed nine academics to undertake new research supporting the EPSRC Future Manufacturing Research Hubs in digital biomanufacturing, intensified and sustainable bioprocess technologies, and process analytical technologies.
- **CE** appointed eleven academics in areas of electrochemical engineering, product & process systems engineering, catalysis and reaction engineering, molecular and engineering thermodynamics, and nature inspired engineering.
- **ME** made fourteen strategic appointments (7 professors, 7 lecturers) to enhance its activity in biomechanical engineering (medical robotics, cellular mechanobiology), materials (energy, additive manufacturing) and marine research (environmental oceanography, fluid-structure interaction).
- **OMS** created four new academic posts, including a lectureship to launch new research developing core technologies for real-time monitoring of pain biomarkers.

This unit is also supported by 63 teaching-only staff, which helps reduce the teaching loads of early-career researchers, and academics on externally-funded fellowships.

UCL's engineering community benefits considerably from visiting scholars, many funded by prestigious Fellowships. For example, **FES** hosted 13 postdoctoral MSCA Fellows (€2.5M), and partnered in 14 Innovative Training Networks (total €49M, UCL portion €5.9M) hosting ~50 early career researchers to advance their careers through training and mentorship. **FES** also hosted academic and industrial visitors from ANU Australia, City University Hong Kong, Duke University, Keio University, National University of Singapore, DSTL, Leonardo, and many other institutions.

2.2. Staff development

All new staff are subject to a probationary period: three years for permanent academics, and nine months for others. Regular review meetings are held with line managers to ensure objectives are set and met, and all academic staff are assigned a mentor, separate from their line manager, with whom they meet regularly to receive guidance on career development.

UCL offers a comprehensive programme of staff development and training (see REF5a). We systematically encourage our staff to take advantage of these opportunities and to undertake roles within our engineering community that will further their careers.

UCL operates strict recruitment policies regarding equality and diversity (section 2.4), and all staff involved with recruitment receive training. We recognise that gender imbalance is a particular problem in engineering disciplines. The proportion of academic staff submitted to this unit who are female is 22.5%, and we have seen a substantial increase in the number of women recruited to senior roles, including two heads of department and eight (of 12) **FES** Vice Deans. During the assessment period, 17 out of our 56 promotions to professor (30%) were female, and the proportion of female research staff in engineering increased from 20% to 25%. While these trends are encouraging, we continue to proactively pursue means of achieving a much better gender balance (section 2.4).

Our annual staff appraisal scheme includes an assessment of career development needs and readiness for promotion. Staff are invited to discuss their case for promotion with their line manager, mentor, and/or head of department, and departments also review and identify promotion candidates. For cases not approved to go forward to UCL's annual promotions process, the head of department advises the individual on ways to strengthen their case. There were 141 senior promotions across this unit during the period of assessment.

We have fully implemented the UK Concordat to support the Career Development of Researchers. Following probation, postdoctoral researchers are employed on open-ended contracts, and salary flexibility under the unified pay spine enables us to ensure recruitment and retention of key staff. Through appraisal and mentoring we help staff explore career options. For those pursuing academic careers, we enable them to acquire teaching experience and assist with applications for research fellowships. We help those inspired to work in industry by exploring opportunities through our extensive industrial links, including our spin-outs.

We encourage sabbatical leave (of up to one year) particularly when this can help develop collaborations, as exemplified by these examples:

- Dr. Watts spent a 6-month sabbatical with Microsoft Research Cambridge in 2016 to pursue a collaborative project on optical networking.
- Dr. Mitrofanov joined the Center for Integrated Nanotechnologies, Sandia National Laboratories, for 6 months in 2017. This established new UCL research on low-temperature THz near-field spectroscopy and imaging.

We also support our staff with longer-term placements. Current examples include:

- Prof. Burriesci is seconded for 3 years to create a new bioengineering research division at the Ri.MED Foundation (Italy). This supports translation of his technologies into clinical practice, while establishing new collaborative networks in Europe and USA.
- Dr. Hanson is seconded 50% to industrial consultancy since 2018 to facilitate new collaborations with major food manufacturers (including Abbott, Brakes, Nestlé, Nutricia), developing and refining products for specialised diets.

2.3. Doctoral Training

This unit operates MRes, MPhil, EngD and PhD Programmes supporting over 900 research students, the majority of studentships being collaborative with industry or other research organisations. Since 2014 we have had a strategic drive towards four-year instead of three-year degrees, and a greater emphasis on doctoral training programmes (DTPs). An increasing number of students now elect to follow a four-year DTP, starting with a one-year MRes. The MRes typically involves taught modules, one or more laboratory projects, and transferable skills training. Our research strategy is supported by eight EPSRC Centres for Doctoral Training (CDTs):

- Bioprocess Engineering Leadership;
- Delivering Quantum Technologies;
- Emergent Macromolecular Therapies;
- Intelligent, Integrated Imaging in Healthcare;
- Mathematics & Physics in the Life Sciences & Experimental Biology;
- Connected Electronic and Photonic Systems (with Cambridge University, led by UCL);
- Advanced Characterisation of Materials (led by Imperial College);
- Compound Semiconductor Manufacturing (led by Cardiff University).

Other studentship support comes through our EPSRC Doctoral Training Partnership funds (engineering is UCL's largest recipient), CASE awards, two EngD programmes, and industry.

In accordance with our research strategy (section 1.2.2), and as exemplified by our CDTs, many students are engaged in cross-disciplinary, inter-departmental or inter-institutional research. We also strategically allocate some of our studentships to stimulate cross-disciplinary projects. Many students pursue projects requiring them to perform significant proportions of their research at institutions such as CERN, NPL, DSTL and Boeing. Recent CASE awards have enabled students to work with companies including Rolls Royce, Thales, BAE Systems, and Silixa.

2.3.1 **Admissions**

Research students are recruited through a combination of advertising (e.g. New Scientist, IET Engineering & Technology, findaphd.com), careers fairs, targeted mail campaigns, and other mechanisms. **FES** runs twilight sessions to encourage final-year undergraduates to consider doctoral training, and our best graduating students are often approached with invitations to apply for studentships. CDTs advertise their programmes annually, regularly attracting applications many times the number of available studentships. Applications are reviewed by panels of academics, and shortlisted applicants are interviewed (in person or online) by at least two members of staff.

Early-stage academics are often supported by preferentially allocating studentships to them, in addition to studentships provided as part of start-up packages.

2.3.2. **Support**

We provide a hierarchy of support for research students. Each is assigned primary and secondary supervisors (and sometimes tertiary supervisors, such as clinicians, industrial collaborators, or other stakeholders). Students and supervisors receive support and guidance from Departmental Graduate Tutors and Faculty Graduate Tutors. Meanwhile departmental and CDT administrators handle routine student issues, publicise career opportunities, and interface with UCL's Registrar's Division and Doctoral School.

Engineering research students integrate into the life of their department and faculty through regular social events and research seminars. PhD students are based within a research group, working alongside postdoctoral researchers and academics on a daily basis.

UCL's Doctoral Education Strategy, which provides an institutional framework for research student training, has been developed by UCL's Doctoral School, and is aligned with UCL's strategies for Research, Innovation & Enterprise, and Global Engagement. The Doctoral School is responsible for developing (and monitoring adherence to) Codes of Practice, and for providing support and professional development opportunities to all research students (including funding and scholarships, pastoral issues, and teaching opportunities). The Doctoral School also ensures students have

access to advisors providing confidential advice and support on issues concerning welfare, disability, and mental health.

2.3.3. Skills Training

The Doctoral School runs a comprehensive Doctoral Skills Training Programme for research students, with >100 courses on diverse topics designed to expand generic research competences and transferable skills. This includes training in: Research Organisation & Governance; Communication, Influence & Impact; Personal Effectiveness; and Leadership Skills. Courses are also available from partner institutions in the Bloomsbury Postgraduate Skills Network. Research students can also attend our masters-level technical modules (hundreds across the unit). All research students are expected to undertake training opportunities for the equivalent of two weeks per year, and a training record is maintained via the online Research Student Log (section 2.3.4).

Doctoral students are strongly encouraged to engage with the world beyond academia. For example, we place students with collaborating companies via Knowledge Transfer Studentships to pursue projects of major industrial relevance; this benefits our academics by strengthening industry links, the company by supporting development of new technologies, and the students, many of whom are employed by the company following their PhD. Student involvement in public engagement and outreach include appearances on the Guardian's Science Weekly podcast, radio interviews, contributions to the Cheltenham Science Festival, and many visits to primary and secondary schools. Students have also contributed to the Royal Society Summer Science Exhibition, the Big Bang Fair, the Manchester Science Fair, and to STEMNET, an organisation established to inspire young people in STEM subjects.

FES runs three-day retreats for first-year doctoral students at Cumberland Lodge, a conference centre in Windsor Great Park. These provide training in research ethics, presentation skills (delivered by a theatre group, Artesc), entrepreneurship, and personal resilience. They also build cohesiveness across the cohort. All students are invited, along with staff members and external speakers, and the programme maximises opportunities for informal interaction. Approximately 180 students attend the retreats each year, with >90% rating them Good or Very Good. Typical feedback includes "*Cumberland Lodge was a helpful experience for communication and networking"; "Thoroughly enjoyed it – every aspect"; "Very useful to meet new friends and build a good professional network. Really useful courses and well organised*". The format strongly encourages interaction between students from different departments. We will extend these sessions by developing more programmes like ConceptionX (section 1.2.3) for students, covering specialist topics such as entrepreneurship.

The **IHE** have established cross-faculty initiatives to nurture early-stage researchers through a dedicated Careers Delivery Group, which research students can join to build leadership and organisational skills. This is supplemented by resilience and skills-building workshops in collaboration with the Academic Careers Office, and by dedicated early-career sessions at **IHE** Symposia. **IHE** also run a Travel Bursary Award scheme to support conference attendance, and an annual Impact Fellowship scheme where fellows (fourteen selected in 2020) receive personalised mentoring and secondment opportunities and are supported to deliver outputs engaging with policy, media, the public, and other stakeholders.

FES runs interdepartmental seminars with speakers from industry and academia, and skills-focussed workshops, and all departments run specialised research seminars.

2.3.4 Progress Monitoring and Assessment

All PhD students are initially registered for an MPhil or MRes degree, and each must maintain an online Research Student Log which requires them to follow a strict schedule of progress monitoring and assessment, including a report and updated research plan every three months during the first year, and every six months thereafter. Each report and plan is reviewed by primary and secondary supervisors. All students undergo an assessment process (involving a written report and oral examination) before transferring their registration to PhD, typically during their second year. The exam identifies any students failing to meet the necessary criteria for a PhD, and/or those who may decide that undertaking a PhD is not appropriate for them. Students who fail to attain the standard required to transfer are allowed a second attempt within six months.

2.3.5 Research Supervision

UCL requires all academic staff to undergo mandatory training before they can undertake PhD student supervision, including attending a workshop "Developing as a UCL research supervisor." Inexperienced supervisors are also required to serve as a secondary supervisor for at least one year before adopting the role of primary supervisor. UCL provides extensive guidance on good practice for all aspects of research student supervision, including an online "Good Supervision Guide" written by a UCL PhD student.

2.3.6 Research Student Achievements

Over a seven-year window, which takes into account both F/T and P/T study, 87% of doctoral students successfully graduated. They are in high demand post-graduation, with many taking up academic careers as postdoctoral researchers and often continuing to permanent academic positions at leading institutions. Several graduates have been awarded prestigious RAEng (Mehonic 2017, Lavery 2017), UKRI (Balakier, 2018) and other fellowships. Approximately one third of students join leading engineering, manufacturing and IT industries (e.g. Rolls-Royce, BAE Systems, Procter & Gamble, Nestlé Jacobs, BT, Coherent, Nokia, Arup, GSK, etc.), with some occupying key positions in start-ups (Baeriswyl, CEO & founder of *Magic Carpet AI*) and other companies (Bhattacharya-Ghosh, Chief of Staff to CEO at Mercedes-Benz). Our remaining doctoral graduates are impacting society through careers in areas such as healthcare, government, finance and policy. The UCL Careers Service offers one-to-one advice sessions with employment specialists, and **FES** also employs both industry-facing and student-facing specialist advisors.

Many of our doctoral students have won major prizes for their research, including: ESRF Young Scientist 2020 and IChemE Young Chemical Engineer 2018 (Finegan); IMarEST's Denny Medal 2017 (de la Fuente); IMechE Best Thesis 2016 (Alimohammadi). Many doctoral students have also been awarded entrepreneurial grants, often supported via the Conception-X programme (e.g. £150K Innovate UK Smart Grant for "an ingestible medical device for chronic disease monitoring", awarded to Phoebe Heseltine).

2.4 Equality and Diversity

2.4.1 EDI culture and training

UCL operates under a five-year Equality, Diversity & Inclusion (EDI) Strategy, to "*foster a positive cultural climate where all staff and students can flourish*." This was supplemented in 2020 with an Equity & Inclusion Plan to address the impact of the Covid-19 pandemic on sectors of the UCL community resulting from existing structural and historical inequalities. Every UCL department has a Departmental Equal Opportunities Liaison Officer, who monitors the implementation of equal opportunities policies and provides advice to students and staff.

Since 2014, *Engineering@UCL* has been heavily focused on increasing female representation at all levels, and this is evidenced by multiple Athena SWAN Silver (**BE**, **CE**, and UCL Division of Medicine) and Bronze awards (**CEGE**, **EEE, LCN, MPBE** and UCL Division of Surgery & Interventional Science). The careers of female early-career researchers are supported through *Women in Research, Women in Leadership* and *Senior Women in Leadership* workshops (part of UCL's Researcher Development Framework). Since 2015, thirty-one **FES** women have attended these programmes. In addition to the appointment of two female heads of department, two departments (**EEE**, **MPBE**) have observed growth in the proportion of female academic staff by over 6%, and four (**BC**, **CE**, **EEE**, **MPBE**) have observed growth in the proportion of female research staff by between 5% and 10%. We have also been highly proactive in encouraging individual female researchers to apply for Fellowships, and since 2018 women have won three of the five RAEng Research Fellowships and two of the four UKRI Innovation Fellowships awarded to this unit.

Other **FES** initiatives include creation of a Carer's Fund to cover childcare costs incurred by travel to conferences or other professional events, and widespread adoption of core working hours (10:00-16:00) to support those working flexibly or who have parental/caring responsibilities.

All returned staff have undergone Unconscious Bias training at least once during the reporting period, and we have held seven mandatory "Where Do You Draw The Line?" workshops, which raise awareness of bullying and harassment.

In 2019, **FES** appointed a Vice Dean for EDI (Prof. Diaz) and in 2020 launched a new EDI strategy following faculty-wide consultation. This focuses on "belonging", with a goal to create an equitable, transparent, accountable and inclusive environment where everyone is valued and empowered to make an impact. A cornerstone of the strategy is the creation of departmental EDI committees, with representation from all categories of staff and students, each led by an EDI Director. The **FES** EDI Implementation Group, consisting of departmental EDI Directors and chaired by the Vice Dean for EDI, meets six times per year to review progress.

The EDI strategy has six objectives, each with an action plan reviewed annually. These objectives establish standards and reward EDI citizenship, increase representation of minority groups, and promote an inclusive and equitable environment. They also directly address discrimination and create opportunities for participation and empowerment. Our strategy's goal is for **FES** to become the UK's leading engineering faculty in terms of EDI best practice. The strategy has already achieved several key milestones, and led to a variety of initiatives:

- In 2020, we organised a "*Summer of learning: Race inequality and black lives matter*" programme that concluded with a whole day event addressing racism, attended by >250 staff. As part of this event, **FES** committed to Race Equality pledges to: increase representation of Black, Asian and Minority Ethnic (BAME) staff in key senior roles; use fair recruitment specialists for all senior positions; create a Race (Equality) Group (including academics, students, and professional support staff) to address the BAME attainment gap and support inclusive curriculum activities.
- We conducted training seminars on EDI topics such best recruitment practices for inclusive shortlisting and interviewing, microaggressions, allyship, and the added value of diversity.
- We worked with >300 Chinese students to address specific wellbeing issues, which resulted in recommendations for adjustments to extenuating circumstances, new wellbeing checkpoints, and improved management of mental health issues.
- We created and funded a Neurodivergent Staff Network.
- We introduced a common EDI baseline questionnaire across **FES** to measure progress on objectives.

Approximately 250 new academic, research and teaching posts will be recruited for the **UCL East** expansion by 2023 (section 3.2.3), the majority within **FES**. UCL is committed to equity and diversity in recruitment of this new cohort. Specific measures include recruitment best practice training, development of equity-focused job adverts, job descriptions and recruitment procedures. Wherever possible, UCL's Fair Recruitment Specialists will be used to provide visible ethnic diversity on interview panels and to reduce potential bias during shortlisting.

Our engineering community is closely involved with the charity *In2scienceUK* which empowers young people from low income and disadvantaged backgrounds to pursue education and careers in engineering and science. For example, in 2019, thirty-three year-12 students from disadvantaged backgrounds (93% had no family history of higher education, and 61% were eligible for free school meals) completed a 2-week summer work placement in six of our engineering departments.

2.4.2 REF staff inclusion strategy

We adopted a multi-step process for staff output selection. All eligible staff initially nominated up to five outputs and provided supporting narratives. Panels of senior academics within each department then reviewed and rated each output, sometimes with the assistance of reviewers outside the department. The long list of nominated outputs was then processed, with each staff member allocated at least one output, remaining outputs being allocated in descending rating order to give an average of 2.5 and a maximum of 5. At this point the output allocation was analysed according to gender, ethnicity, disability, age, nationality, and sexual orientation. An appropriately diverse panel of academics then sampled outputs from different departments to calibrate any rating imbalances across different disciplines, and to ensure an appropriate distribution across protected characteristics.

Women represent 22.5% of the staff submitted to this unit. While female and male HESA 3 academics were equally likely of selection, men are somewhat more highly represented in HESA 2 roles, reflecting that holders of prestigious early career Fellowships are more likely to be male (although this imbalance is subject to proactive measures with recent success as reported in section 2.4.1). Meanwhile 21.7% of submitted staff identify within the BAME group. Data reveals that white staff have had a greater likelihood of selection than BAME staff, underlining why a major focus of EDI initiatives within our engineering community is addressing the BAME attainment gap.

An analysis of the outputs selected for this unit reveals that:

- male and female staff have equal likelihood of output attribution;
- BAME staff are 5% more likely to have an output attribution than any other ethnic group;
- staff aged between 55 and 64 are 12% less likely to have an output attribution than all other age groups. The likelihoods for other age groups are approximately equal.

Only 2.2% of staff identify as disabled, and thus the statistics are not sufficiently reliable to infer trends.

We recognised that the process of output selection may cause anxiety to some staff and through a number of forums (e.g. faculty and departmental meetings, newsletters, REF workshops, etc.) it was emphasised that the REF process was not relevant or considered during staff appraisal or applications for promotion.

3. Income, infrastructure and facilities

3.1. Income

3.1.1. Research income strategy

Institutional research income strategy is driven by the Office of the Vice Provost for Research, which is responsible for initiatives to foster cross-disciplinary collaboration and facilitate relationships with policymakers through the UCL Public Policy programme. Research income strategy within each engineering theme is developed by departmental research committees, informed by a broader strategy set by the faculty management committee, which prioritises resources to support research initiatives with appropriate diversification of funding across research councils, charities, and industry.

Departmental committees, as well as individual researchers, work directly with the BEAMS Research Coordination Office (RCO), which serves two vital roles: providing guidance on matching our strategic priorities for research to funding opportunities, and coordinating applications for large-scale funding calls and fellowship schemes. They also distribute monthly newsletters to academic research staff, which identify funding calls, and maintain up-to-date funding information online. For competitive bids for Research Centres, capital equipment and other large programmes, the RCO run triage exercises to prioritise proposals including internal assessments by panels of senior academics. Where appropriate we bring research groups together to work collaboratively on larger bids, drawing on expertise across UCL. In selecting bids to go forward we take account of how the activity relates to research strategy. For large grants such as Programme Grants or prestigious ERC awards we run mock interviews, generally chaired by previous successful applicants. The RCO also coordinate internal shortlisting and selection of candidates for restricted fellowship schemes, and arrange training sessions, mock panel interviews, and support with writing proposals for fellowship candidates. Meanwhile, the UCL Research Finance Office ensures all proposals and costings comply with the funders' and UCL's procedures.

In 2020, **FES** undertook a comprehensive and strategic review of the sustainability of UCL engineering research income, led by the **FES** Vice-Dean (Research). We developed a financial model that uses data on research income, student numbers and cost drivers to model the sensitivity of our research funding to changes in the funding landscape and to inform income strategy. As a result, we are in the process of reviewing our policies on the recovery of the full economic costs (FEC) of research across different categories of funder (research councils, charities, industry, etc.) to ensure ongoing sustainability.

In 2018, UCL undertook a major overhaul of its research support, including contracts, pre-award costing, project management, and post-award support. In February 2021 **FES** piloted a new structure which includes a new Research & Innovation Support Office. This provides researchers with a single point of contact to navigate the increasingly complex research funding landscape and enables researchers to concentrate on research rather than the supporting processes.

3.1.2. Research grants

Our total research income during the assessment period was £265M, income being defined as expenditure on a research award. This is an average annual income of £37.9M, or £147.8K per FTE per year. Between 2014 and 2020, annual income increased from £29M to £41M. Our primary income sources are EPSRC (£122M), EU government (£38M), UK charities (£30M), UK central government (£19M), and UK industry (£15M). Major awards received during this period of assessment include:

- £10.5M EPSRC Future Targeted Healthcare Manufacturing Hub.
- £4.9M EPSRC Programme Grant, “Unlocking the capacity of optical communications (UNLOC)”.
- £6.1M EPSRC Programme Grant, “Transforming networks - building an intelligent optical infrastructure (TRANSNET)”.
- £6.1M EPSRC Programme Grant, “Quantum dot on silicon systems for communications, information processing and sensing (QUDOS)” with Cambridge, Cardiff and Southampton Universities.
- £6.5M EPSRC Programme Grant, “HyperTerahertz: High precision terahertz spectroscopy and microscopy” with Leeds and Cambridge Universities.
- £7M EPSRC Programme Grant “Non-Ergodic Quantum Manipulation”.
- £5M EPSRC Centre for Nature Inspired Engineering.
- £11M EPSRC Centre for Process Engineering Prosperity Partnership.
- £2.6M EPSRC Centre for Collaborative Healthcare Innovation through Mathematics, EngineeRing and AI (CHIMERA).
- £13.5M Wellcome Trust/EPSRC Centre for Interventional & Surgical Sciences (WEISS).
- £5M EPSRC Prosperity Partnership award with Nikon.
- £5M Pears Foundation donation to create the Institute of Immunity & Transplantation.

3.2 Infrastructure

The majority of the reported engineering research activity occurs on the main UCL campus in Bloomsbury, while a sizeable minority is based at multiple Centres, Institutes, and hospitals adjacent to the campus or in the surrounding Greater London area. The strategically-managed growth of engineering research at UCL has required substantial investment in infrastructure, which is managed by the UCL Estates Division. In 2014 UCL began a ten-year £1.25 billion investment programme known as *Transforming UCL*, of which Engineering has been a substantial beneficiary.

Engineering@UCL are also major stakeholders in the £528M **UCL East** development in Stratford, and the Person-Environment-Activity Research Laboratory (**PEARL**) in Dagenham, funded by a £51M investment (£9M from EPSRC, £42M from UCL).

3.2.1. London Centre for Nanotechnology

The London Centre for Nanotechnology (**LCN**) occupies a purpose-built facility on the UCL campus containing state-of-the-art clean-room, characterisation, fabrication, manipulation and design laboratories, with additional facilities based at Imperial College and King’s College London (KCL joined **LCN** in 2018 as part of a strategic expansion). Major upgrades were performed to **LCN**’s facilities in 2016 as part of an £8.5M EPSRC capital equipment grant, which provided a 100kV electron beam lithography tool for advanced pattering of nanostructures and other state-of-the-art equipment. This was supplemented by a £3.2M estates programme to enhance the cleanroom and refurbish other **LCN** laboratories.

3.2.2. Here East

Here East at Queen Elizabeth Olympic Park in Stratford is a unique collaboration between **FES** and the UCL Bartlett Faculty of the Built Environment. The 6000m^2 facility supports engineering research

in areas of infrastructure, transport, robotics, healthcare, manufacturing, and environmental measurement. For example, the space allows for large-volume robotics for manufacture, inspection and testing at factory scales, as well as advanced surgical robots. Meanwhile, a structures & environmental lab provide unique facilities for large-scale testing, such as fatigue loading and cyclic mechanical-environmental loading of structures.

3.2.3. UCL East

The launch of **UCL East**, a new campus at Queen Elizabeth Olympic Park, is a key component of the research strategy for *Engineering@UCL*. The development is currently 50% complete, and on track to open in 2022/23. Financed by £428M from UCL and £100M from government, **UCL East** will eventually accommodate ~4000 new students and 260 new academics. The first two buildings (Pool Street West and Marshgate) will provide 50,000m^2 of space.

UCL East provides *Engineering@UCL* with opportunities to pursue new interdisciplinary approaches to research, enterprise, and education, and explore issues as diverse as sustainability, manufacturing, urbanisation, healthcare, heritage and inclusivity. The campus will consist of 12 new academic centres, with the four listed below playing a fundamental role in the implementation of our strategy for research and impact.

- **Advanced Propulsion Laboratory:** Championing new technologies to create the next generation of battery and fuel cell vehicles and hybrid systems, the 700m^2 laboratory will focus on battery manufacture and battery, system and fuel cell testing. An additional 1500m^2 pavilion is being designed for full-scale engine and vehicle testing.
- **Manufacturing Futures Lab:** This will focus on manufacturing for a net zero, carbon-constrained future. The 1500m^2 lab will provide multi-disciplinary facilities for knowledge-based manufacturing research, with emphasis on (bio)pharmaceuticals, chemicals, and next generation materials.
- **Institute of Making:** A new multidisciplinary open-access workshop will provide 1000m^2 of flexible space for student-led fabrication projects with a wide range of materials and tools, supported by specialist equipment rooms.
- **Experiential Learning & Research Hub:** This will explore innovations in engineering education to create our next generation of engineers. The hub will provide flexible teaching spaces including 650m^2 of wet labs and 500m^2 of dry labs, and 700m^2 to support the launch of a new programme in design engineering.

FES is developing several new teaching programmes to support **UCL East** activities, including Undergraduate and Masters courses in Engineering Finance, Robotics, and Advanced Propulsion.

3.2.4. Person-Environment-Activity Research Laboratory (PEARL)

PEARL is due to open in April 2021 as a much-expanded replacement for the highly successful **PAMELA** (section 1.3.3) based in Tufnell Park. The new facility will be 15 times larger, with a capacity of 4000m^2. It will enable full-scale interactions between people and infrastructure, allowing whole streets or rail stations to be simulated, and facilitate new transformative research in sustainable human/built environment interaction. **PEARL** will also include a 500-seat theatre and public viewing gallery. It will provide a major boost to engineering research activity, which has already benefitted from the transfer of heavy structures and larger scale robotics work from the UCL Bloomsbury campus to **Here East**, with a new floor area of 500m^2.

3.3. Facilities

Engineering@UCL enjoys world-class research facilities, and has benefitted from an investment of £39M during the period of assessment.

A £15M refurbishment of Charles Bell House, adjacent to the UCL campus, was completed in 2018 as a home for the £13.5M Wellcome Trust/EPSRC Centre for Interventional and Surgical Sciences (**WEISS**, section 1.3.6). The Centre contains several floors of offices, meeting spaces, and specialist laboratories, including a mock operating theatre with x-ray and other imaging systems.

Major facilities projects in **EEE** include a £4.9M EPSRC award to lead the National Dark Fibre Facility, £1.4M as a partner site in the EPSRC Semiconductor Epitaxy Facility, £1.8M as a spoke in the EPSRC funded Semiconductor Manufacturing Hub, and a £2.6M investment in MBE facilities.

New facilities provided for the **CNIE** (section 1.3.2) include a world-class SAXS/WAXS system, and a 3D nanoprinting system. Meanwhile, **EIL** (section 1.3.2) received a £4.6M investment in equipment, including an x-ray tomography suite with 3 CT scanners, an AFM for electrochemical analysis in inert atmosphere, an SEM, a Raman microscope, and an x-ray diffractometer.

As part of a 2014 Materials Hub initiative, we refurbished eight chemical engineering labs providing 475m^2 of space for a state-of-the-art x-ray materials characterisation facility, expansion of the **CNIE** and **EIL**, and labs for research on soft materials and catalysis. Several engineering departments benefitted from a major refurbishment to create a new Biomaterials Hub in 2014, which includes a large clean room and specialised material fabrication facilities.

The departments of **CE** and **BE** share a 300m^2 Rapid Prototyping & Fabrication workshop, completely refurbished during the assessment period. It houses eight CNC instruments and a 3D printer to manufacture bespoke items with length scales from 0.1mm to >10cm. Six technicians provide expertise in CAD design and machining.

In 2019 we launched MechSpace, a new 1100m^2 student hub in London's King's Cross to support design and construction projects. This enabled the UCL Ventura CPAP project to proceed during the first UK Covid lockdown by providing accessible self-contained facilities.

A recent £2M investment provided our civil engineers a 150m^2 floor with large rigs for cyclic fatigue testing of full-size bridge components and a 160m^2 environmentally controlled chamber to investigate the combined effects of various natural hazards.

There have also been major additions to the research facilities for UCL's hospital-based engineering community. The **INM** benefitted from investment in multimodality imaging facilities, including Siemens and GE PET/CT systems, a Siemens PET/MR system, and two GE SPECT/CT systems. **SB** received a £1M investment for a scanning electron microscope and a laser confocal microscope, while extensive facilities for microbiology and cell transfection were added to **TI**'s resources. Recent **CMI** investments include a system for creating hyperpolarised pyruvate for contrast-enhanced MRI.

Our engineering research community benefits considerably from the support of the UCL Research Software Development Group (**RSDG**), consisting of 24 research software engineers with expertise in many computational techniques, technologies, languages and tools. When founded in 2012, **RSDG** was the first of its kind in the UK, and the UCL model is now being replicated by research-intensive universities across the UK and internationally. **RSDG** collaborates with our researchers to build and maintain reliable and efficient scientific software, focusing on compute- and data-intensive software engineering.

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

4.1 London collaborations

London is a major research centre and a significant draw for international talent. UCL hugely enjoys its close proximity to learned societies (e.g. RAEng, Royal Society), outstanding research institutes, and other exceptional scientific universities. *Engineering@UCL* directly benefits from this environment, including the establishment of the **LCN** (with Imperial and King's), and our many collaborative projects with institutes such as the NPL (including **MPBE** and **INM**), the Alan Turing Institute (including staff holding joint positions as Turing Fellows, such as Profs. Rio and Atkinson), and the Francis Crick Institute (e.g. **ME**'s biomechanical engineering group).

4.2 Collaborations with other leading institutions

Collaboration with the world's leading researchers is fundamental to our research strategy. The majority of research staff are members of one or more multi-institutional collaborative projects, and many such projects are led by our academics. International collaborations commonly enable

researchers to leverage EU and/or other non-UK funding, and our success is evidenced by the £38M EU funding received during the REF period. Examples of many large collaborative projects we lead include:

- *VaxHub*: Oxford, Imperial, Leeds, London School of Hygiene & Tropical Medicine.
- *Future Targeted Healthcare Manufacturing Hub*: Imperial, Manchester, Warwick, Nottingham, Loughborough.
- *TRANSNET Programme Grant*: Cambridge, Oxford, Leeds, Bristol, Southampton, Aston, Lawrence Livermore Laboratory, Los Alamos National Laboratory.
- *UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC)*: Cambridge, Imperial, Cranfield, Loughborough, Newcastle, Birmingham, Bristol, Leeds, Manchester, Oxford, Sheffield, Southampton.
- *The Anchored Muscle Cells for Incontinence consortium*: Instituto Superior Técnico (PT), Queen Mary UoL, Medical University Graz (AT), Aarhus University Hospital (DK), Rouen University Hospital (FR), University Hospital Erlangen (DE), Instituto de Investigacion Sanitaria Fundación Jiménez Díaz (ES), NHS Blood & Transplant, Ttopstart (NL), Bowel Research UK, Consorzio per Valutazioni Biologiche e Farmacologiche (IT).

We host the £2.7M Coordination Node of UKCRIC, providing leadership for the infrastructure research community, with **CEGE** leading all UKCRIC activities associated with people-centred infrastructure design.

The Yale-UCL Collaborative launched in 2009 takes advantage of complementary research expertise, regulatory environments, and resources. Exemplars of this Collaborative are the joint UCL/Yale appointments of Prof. Hirsch (**MPBE**) and Nobel prize winner Prof. Rothman (UCL Institute of Neurology). Prof. Hirsch leads a highly productive collaboration between the Yale Brain Function Laboratory, Prof. Tachtsidis (**MPBE**), and Shimadzu Corporation.

Dr. Altmann (**MPBE**) has a partnership with Stanford University supported by an NIHR01 grant which is part of the Enhancing NeuroImaging Genetics through Meta-Analysis Consortium, where he co-leads the frontotemporal dementia disease working group. Prof. Olivo (**MPBE**) has five EU projects with the European Molecular Biology Lab, Centrum Wiskunde & Informatica (the leading centre for image processing in the Netherlands), Diamond, Microworks (a German microfabrication company), IMASENIC (a Spanish CMOS company) and Queen Mary UoL.

Prof. Hutton (**INM**) collaboration with the Politecnico di Milano, supported by two EC grants, has led to the development of the world's first clinical SPECT/MRI system. Profs. Thielemans (**INM**) and Atkinson (**CMI**) lead the EPSRC-funded Collaborative Computational Project on synergistic reconstruction for biomedical imaging, a network of UK partners focussed on PET/MR image reconstruction. Meanwhile **CMI** provides the Imaging Trials Unit infrastructure for the CRUK-funded National Cancer Imaging Translational Accelerator that links nine UK centres committed to the discovery, validation and delivery of practice-changing clinical imaging biomarkers for cancer patients.

About a third of **CE** academics are members of the multi-institutional Centre for Process Systems Engineering (including deputy director Prof. Bogle) which consists of engineers, mathematicians and molecular scientists working to define and quantify the components that make up complex industrial chemical processes in order to optimize performance. The centre holds an £11M Prosperity Partnership project with the US pharmaceutical company Eli Lilly.

IHE's partnership with the All India Institute of Medical Sciences and Indian Institute of Technology includes joint PhD studentships, collaborative research projects, and annual student exchanges.

Across the unit, many staff have close working relationships with national and international laboratories and facilities. Examples include:

- Prof. Olivo (**MPEB**) collaborates with national synchrotron facilities in France (ESRF), and Italy (ELETTRA), and UK (Diamond),
- Profs. Thielemans and Hutton (**INM**) work with the NPL on quantification and standardisation in nuclear medicine;
- Prof. Mitrofanov (**EEE**) has a long-standing relationship with Sandia National Laboratories;

- Prof. Kenyon (**EEE**) works with A*STAR (Singapore) and Forschungszentrum Jülich on microscopy of nanoelectronic devices;
- Prof. Lee's group (**ME**) is based at the Harwell Campus, working with Diamond Light Source and the other UK facilities (section 1.3.5).

Reported staff hold honorary positions at many institutions, including professorships at Universities of Edinburgh, Imperial College, Southampton, Hong Kong, Wollongong, Hong Kong Polytechnic, and several across China.

4.3. Collaboration with industry

Engagement between UCL academics and industry is supported by UCL Innovation and Enterprise, which works closely with **UCLB** and **UCLC** (section 1.2.3). Within **FES**, a team led by Vice Dean (Enterprise), Jane Butler, provides dedicated support to our researchers engaging with industry. We have extensive industrial collaborations (table 1), from SMEs to large multinationals. We engage through numerous mechanisms, including sponsored PhD projects, CASE awards, consultancy, secondments, joint research and development projects, and IP licensing. In many cases our large projects involve multiple industrial partners. Examples include:

- *Coherent Terahertz systems Programme Grant*: IBM, Airbus, Agilent, Teraview.
- *TRANSNET Programme Grant*: BT, Alcatel, Microsoft, Sumotomo, Oclaro, Corning, Eblana, Mistubishi, Deutsche Telekon, Ericsson.
- *Future Targeted Healthcare Manufacturing Hub*: AstraZeneca, GSK, Merck, Roche, Sartorius, Eli Lilly, Fujifilm, Pfizer and 36 others.

We often use industrial collaborations to develop and/or exploit new IP. In **MPBE**, for example, Prof. Holder and Dr. Aristovich's work with Galvani Bioelectronics has so far yielded seven patent applications. Alternatively, existing IP can be taken up commercially under license, such as Dr. Endrizzi's patent on dark-field imaging, now being developed into a commercial product.

CEGE currently have 16 industry funded PhDs/EngDs. Prof. Jones was scientific coordinator of the EU CREATE project investigating reduction of private car usage, collaborating across three European Universities, four industrial partners and the EUROCITIES network of major cities. **CEGE**'s 3DImpact Group lead metrology for the Airbus/Aerospace Technology £27m Airbus Wing Integration project at Filton, for which Airbus have loaned an A321 wing. The group has developed large volume metrology inspection systems for wind tunnels at NASA Langley, digital manufacture with Airbus, and infrastructure monitoring with Arup.

Much of **TI's** research involves close collaborative links with industrial partners, such as Prof. Cheema's work with Lonza Biologics to develop 3D cancer models.

Information & Communication Engineering research (**EEE**) is supported by ongoing collaborations with multiple partners including Adobe, BBC, Huawei, Google, and Dimension UK.

The **LCN** has close collaborative relationships with the broader nanotechnology research and industrial communities. As the world's only such facility located in the heart of a metropolis, the **LCN** has superb access to corporate, investment and industrial partners.

4.3.1. Contributions to the economy

We have been increasingly involved in establishing start-ups to exploit research outputs. **UCLB** have assisted our submitted staff to launch 12 new start-ups during the period of assessment, which currently employ 99 individuals and have so far generated a turnover of £12M. This is in addition to our spin-outs established before 2014.

Prof. Pankhurst (**MPBE**) is co-founder of three spinouts: *Endomagnetics* (2007), *Resonant Circuits* (2009), and *MediSieve* (2014), which currently employ >25 FTEs. *Endomagnetics* recorded an annual turnover in 2017/18 of over £6M, and made the 2020 Sunday Times *Tech Track 100* list of technology companies with fastest growing sales.

Our academics also sell technology directly to other users under contracts negotiated by **UCLB**. Prof. Beard (**MPBE**) received numerous requests for microresonator-based ultrasound sensors reported in a 2017 Nature paper, which he now supplies to the Medical University of Vienna,

University of Grenoble and Kings College London under collaborative agreements. Similar arrangements enabled near-infrared brain imaging systems to be sold by Prof. Hebden's (**MPBE**) team to users worldwide (generating over £900K) before the activity was spun-out as *Gowerlabs Ltd*. in 2015. Total sales have now exceeded £2.8M. Subsequent collaboration with *Gowerlabs*, funded by a 2016 Innovate UK SMART grant, resulted in a new generation of technologies released as a commercial product in 2019.

The Future Targeted Healthcare Manufacturing Hub (**BE**; section 1.3.1) has produced substantial costs savings in manufacture and brought therapies to market more quickly. UCL estimates the value to a biopharmaceutical company to be US$50-100M, while *MedImmune* (a key industrial collaborator with UCL) believes this estimate is conservative.

BE also produced several outstanding spin-outs including *Synthace* (raised >£30M, with 80 FTEs), *OriBiotech* (raised US$20M), and *Puridify* (17 FTEs). *Puridify* was GE Healthcare's highest value acquisition in 2017, at £14.8M, and customers report that the product yields a 6-fold increase in productivity.

Prof. Rafiq (**BE**) developed commercial bioreactor platforms for human stem and T-cell production for advanced therapies. This led to Hitachi Chemical Advanced Therapy Solutions developing the *ambr®15* and *ambr®250* bioreactors, and a US$2M investment.

Prof. Angeli (**CE**) developed a rheological model for optimized manufacturing of oral healthcare products. This has been implemented by GlaxoSmithKline for manufacturing of *Sensodyne*, leading to 16% reduction in production time.

Profs. Ziebart and Groves (**CEGE**) developed core vehicle positioning technology now used in the Uber app worldwide (65 countries and 700 cities).

Spin-out *Bramble Energy* (**CE**; section 1.3.2) received £5M of venture capital investment.

The risk models developed by our **EPICentre** (section 1.3.3) are used by the World Bank and many companies such as Guy Carpenter, Willis Reinsurance, and AIR Worldwide to produce and calibrate pricing of insurance products (exceeding a value of €229 billion in Iceland and Morocco). The models have been used to conduct rapid post-disaster assessments, determining deployment of >US$1 billion in emergency funds.

The annual turnover of *Zinwave Ltd*., founded to exploit distributed antenna system research conducted by Prof. Seeds (**EE**), grew from £3.6M in 2013 to £9M in 2018.

Implantable cardiovascular devices developed by Prof. Burriesci (**ME**) led to two commercial products distributed by *LivaNova*, which have generated average annual sales of US$115M between 2016 and 2019.

4.4. Collaboration with end users

4.4.1. Policy

In 2018 we created the Policy Impact Unit (**PIU**) led by former POST Director, Dr. Tyler. While based within **STEaPP**, the **PIU** serves our whole engineering research community. It works closely with researchers to identify policy changes we wish to affect and to develop strategies likely to lead to those changes. The **PIU** organises policy briefings, policy roundtables, and engagement with a broad spectrum of policy bodies, and has been instrumental in agenda-setting for several UK research priorities, including quantum technology, battery technology (through involvement with the Faraday Institution), and the IoT via our leadership of the PETRAS National Centre of Excellence for IoT Systems Cybersecurity. Examples of our recent **PIU**-facilitated engagements with policy include:

- A combined policy roundtable (2019), KTN event (2019) and policy briefing on future computing technologies that resulted in the inclusion of neuromorphic computing on the list of potential inquiries for the House of Lords Science & Technology Committee (2020).
- Policy briefings for the Future Targeted Healthcare Manufacturing Hub and VaxHub.

Other policy work includes:

- Prof. Ziebart (**CEGE**), advisor to UK government Cabinet Office, gave evidence to the BEIS parliamentary select committee and co-authored ministerial Blackett Review on vulnerabilities of satellite navigation technology on critical national infrastructure.
- Prof. Spurgeon (**EEE),** member of the DSTL board, chaired their external review college.
- Prof. Griffiths (**EEE**), chairs the science defence experts committee and provides advice to UK government on air space safety.
- Prof. Torero (**CEGE**), key expert for the Grenfell Public enquiry and advisor on post-Grenfell Toxicity assessment. Serves on Science & Engineering Evidence Assurance Committee.
- Dr. Carlson (**SB**), participation in the Royal Society Pairing Scheme (2016), advising the Secretary for the Prime Minister's Council for Science and Technology, and engaging with parliamentarians and science policy development.
- Prof. Rossetto (**CEGE**), advisor to Chilean Government on strategy for resilience to natural hazards.

4.4.2. Healthcare and Society

Our approach to impact is enshrined within our strategy "to produce real benefit to all sectors of global society in a sustainable and equitable manner" (section 1.2.2).

Our healthcare engineering research maximises clinical impact through an interdisciplinary alliance between engineers and end-users (doctors and patients), and the **IHE** and **WEISS** (section 1.3.6) were established to facilitate strategic new partnerships. Our research groups often include clinically-qualified and other hospital-based staff. For example, three of the submitted **MPBE** professorial staff are practising clinicians as well as engineers.

An exemplar of a successful UCL-led collaboration between engineering and the NHS is Prof. Royle's (**MPBE**) leadership of the London-wide, multi-institution CRUK Radiotherapy Centre of Excellence, a core part of RadNet (a national initiative to advance survival and quality of life for cancer patients). This evolved from Art-Net (a CRUK accelerator) which Prof. Royle also led, to accelerate translation of radiotherapy research. These platforms underpin new co-operations with US and Chinese radiotherapy services, which enable our research to have worldwide impact. An example of societal benefit is the introduction of a multi-disciplinary team approach in a large hospital in Shenzhen, China, which transformed clinical practices and outcomes for patients with gastro-intestinal cancers.

Recently we placed greater emphasis on collaborations that impact global health. For example, Prof. Elwell (**MPBE**) leads brain imaging projects funded by the MRC and the Gates Foundation, with research collaborators in London, Cambridge, Gambia, and India, and engagement with populations in resource poor environments (Gambia and Bangladesh). Her work also includes training of African scientists in neuroimaging and infant development assessment to build local capacity. Dr. Leung (**MPBE**) is collaborating with University of Ghana, Korle Bu Teaching Hospital and Greater Accra Regional Hospital on the development of a smartphone app to diagnose jaundice and anaemia in babies and infants. MRC/Newton funding enables Dr. Leung to collaborate with scientists in New Delhi to collect clinical data to develop the app.

Dr. Ricketts (**TI**) and Prof. Royle (**MPBE**) conceived the *paRTner* radiotherapy global partnership programme, a 50-strong team of NHS staff, with support from the Royal College of Radiologists, Society of Radiographers, Institute of Physics & Engineering in Medicine, and endorsed by the Ghana Ministry of Health. Among many outputs, this led to the creation of a new clinical training scheme and a new professional body, the Ghana Society of Medical Physics. Collaborations with the UK Department for International Development and the Tropical Health & Education Trust (THET) enabled **TI** staff to advise on best practice for equipment donations and repurposing in radiotherapy. This culminated in a toolkit published by THET: "Medical Equipment Donations: Making it Work".

Staff in **TI** regularly engage with patients, the NHS, and regulatory bodies. For example Dr. Ricketts conceived and hosted a 2-day event bringing together colorectal cancer patients with scientists, funders, regulatory bodies and industry to discuss pathways to translation of nanoparticle enhanced radiotherapy.

An **IHE**-led national initiative, *Age Innovation Hub*, uses a digital platform to crowdsource ideas for technologies to support healthy ageing from healthcare professionals, carers, and charities. This has generated ~500 interactions across six challenges, and is already initiating new research.

CEGE's 3DImpact research group have contributed to exhibitions at the Science Museum, British Museum Watt's Workshop, Courtauld Institute, and Tate Gallery. Prof. D'Ayala has worked extensively with Historic Royal Palaces and IBM on conservation projects concerning tapestries at Hampton Court and the Rubens ceiling of the Banqueting House. Meanwhile Dr. Parikh is engaging with several NGOs to develop smart solar solutions for slums and rural communities in Africa and Asia.

4.5. Engagement with the public

4.5.1. Public engagement & media

Involvement in public engagement and outreach is strongly encouraged and is widespread across our engineering community, with support provided by teams at a departmental level, coordinated by the **FES** Vice-Dean for Impact. Annually, **FES** sponsors three researchers to undertake British Science Association Media Fellowships; recent recipients include Prof. Elwell (seconded to the Financial Times), Prof. Zhang (i newspaper), and Dr. Ciric (BBC Radio). Several of our academics have outstanding media profiles. For example, since 2014 Prof. Miodownik and Dr. Czerski have made twenty TV documentaries (a total global audience 5 million); contributed regularly to news and current affairs debates (e.g. on plastic waste) on BBC Radio reaching 3 million listeners (e.g. Today Programme, Start The Week); written three popular science books (total sales >350,000 worldwide, translated into 16 languages); given 90 public talks (live audience 35,000); and won nine prizes for public engagement (Royal Society, RAEng, AAAS, Institute of Physics). Dr. Ciric was the second-most read contributor to *The Conversation* in 2020.

IHE's Engagement Delivery Group provides engagement training to our researchers across healthcare engineering, and supported two of our **IHE** teams exhibiting at the 2019 Royal Society Summer Science Exhibition.

Our Institute of Making runs regular public engagement activities, including an annual 5-day *Festival of Stuff*, which gives the public free access to specialist tuition by master makers.

WEISS conducts extensive public engagement activity, supported by a public engagement manager and regular training of **WEISS** researchers. Since the Centre's launch in 2017, events have reached around 7000 members of the public. Some events are designed to enhance collaboration with patient groups, such as *Nerve Injury Community Day* in 2019 featuring nerve injury patients, with stalls, workshops and talks that explored patient experience. Meanwhile a *Science of Surgery Community Day* in 2019 involved 17 activities (talks, interactive displays, etc.) delivered by 52 researchers to 300 visitors, targeted through connections with local community groups. Other **WEISS** events have reached patients and the public through collaborations with charities, artists and creative facilitators. Examples include interactive digital games to prompt public discussion of the ethics of data-driven healthcare, patient-informed digital pieces inspired by data modelling in cardiovascular surgery, and a series of projects in collaboration with University Arts London.

Public engagement activities within **TI** include cancer awareness activities, school talks and career days, and engagement with the media. For example, Dr. Ricketts contributed to a BBC World News television programme Health Check TV on global cancer care, and she later won a public engagement competition (EPSRC Focus on the Positive) which funded a radiotherapy education development initiative in Ghana. Dr. Ricketts has developed cancer awareness materials for patients in Africa, and undertook a charity-funded tour of Ghanaian secondary girls' schools for one month to promote cancer awareness.

4.5.2. Schools outreach

Engineering@UCL is widely involved in outreach activities to encourage young people into engineering. Every year over 700 **FES** staff and students have been involved in the design and delivery of activities for 5-18 year-olds across London and the UK, which reach up to 8000 school students annually. We have provided personal and online training on engagement, outreach,

volunteering, inclusion and safeguarding for over 450 staff and students, in partnership with UCL Culture, UCL Volunteering Services, and UCL Access & Widening Participation (which supports 400 student STEM Ambassadors in **FES**).

Our 50:50 UCL Engineering Engagement Strategy, which requires all visiting school parties to have equal gender representation, was presented at the European Parliament in June 2019. The Strategy was also featured by UNESCO's Education as an example of best practice in promoting diversity and inclusion. Increased adoption and dissemination of the strategy featured this year in Engineering UK's report "State of Engineering: Gender parity in Engineering".

We offer bespoke STEM engagement programmes in East London tailored to the specific needs of the local schools, youth centres and communities as part of our ongoing commitment to the regeneration of East London and the creation of **UCL East**. In partnership with London boroughs (Camden, Hackney) and the Black Curriculum we offer training to teachers in primary and secondary schools, and are developing inclusive STEM resources that can be embedded in the UK school curriculum.

During the reporting period we have trained >200 teacher coordinators and >1400 teachers from across the UK using online teaching resources developed in partnership with the RAEng, Institute of Physics, STEM Learning UK, and the IET. We also designed and offered teacher placements to support teachers through professional development by working closely with our research staff and students.

We developed a "Meet The Future You" national UK STEM campaign in partnership with Engineering UK and Tomorrow's Engineers. This was piloted on 15,000 children and young people at the Big Bang Fair prior to UK launch across in 2019. The campaign also received support from RAEng, Institute of Physics, STEM Learning, IET, ICE and IMECHE.

UCL Engineering is also involved in the EU STEM Coalition and UNESCO Education, and we are advising the Obama Foundation on community-led online mentoring/tutoring schemes for the *Obama Scholars* programme.

4.6. COVID-19 projects

Engineering@UCL has made major contributions in response to the Covid-19 pandemic. Examples include:

- Ciric (**CEGE**): GOSH anti-COVID-19 infection control using DNA markers.
- Malki-Epshtein, Ciric, Stoesser (**CEGE**): CFD analysis of air flow on London buses enabling return to front-door boarding.
- Baker (**ME**), Shipley (**IHE**): UCL Ventura CPAP project (section 1.3.6). This also generated engagement outputs including podcasts co-created by sixth-form students and features in museum exhibitions (e.g. Science Museum, Design Museum).
- Micheletti (UCL Vaxhub with Oxford): Development of the ChAdOx-1 vector that can be quickly and easily modified for new types of virus. UCL role was to develop a manufacturing platform to produce the vaccine.
- Lee (**ME**), Shipley (**IHE**): Developed an imaging technique to quantify Covid organ injury jointly with ESRF. Now funded by a US$1M Chan Zuckerberg initiative grant.
- Demosthenos (**EEE**): Lung monitoring of Covid.

4.7. Major awards and honours

Over 200 awards and honours were given to staff during the REF period, some of which are highlighted in the tables below.

Table 3: Prestigious Fellowships awarded

Fellowship	Recipients
Royal Society (FRS)	Bayvel
Royal Academy of Engineering (FREng)	Edirisinghe, Lye, Miodownik, Paik, Tyler
IEEE (FIEEE)	Demosthenous, Pavlou, Spurgeon, Wong
Royal Institute of Navigation (FRIN)	Ziebart

Table 4: Honours awarded

Honour	Recipients
Knighthood	Mulgan
CBE	Bayvel
OBE	Edirisinghe, Griffiths, Jones, Spurgeon
MBE	Baker, Miodownik

Table 5: Exemplars of Major Prizes awarded

Recipient	Prize	Awarding body	Year
Bayvel	Clifford Patterson Lecture	Royal Society	2014
Hutton	Marie Sklodowska-Curie Award	IEEE	2014
Barrett *et al*.	Innovation Team of Year	British Medical Journal.	2015
Paik	William Froude Medal	Royal Institution of Naval Architects	2015
Groves	Thurlow Award	Institute of Navigation	2016
Morton	Raymond & Beverly Sackler International Prize in Physical Sciences	Tel Aviv University	2016
Stoesser	George Stephenson medal	Institution of Civil Engineers	2016
Torero	Honorary Doctorate	University of Ghent	2016
Edirisinghe	Chapman Medal	IoM3	2017
Griffiths	Achievement Medal for Radar Engineering	IET	2017
Miodownik	Michael Faraday Prize	Royal Society	2017
Czerski	Lord Kelvin Medal	IoP	2018
Miodownik	Science Communication Medal	Max Planck Institute	2018
Ziebart	Tycho Brahe Award	Institute of Navigation	2018
Ziebart *et al*.	Group Achievement (Geophysics)	Royal Astronomical Society	2018
Pepper	Newton Medal	IoP	2019
Hawkes	Peter Mansfield Medal	IoP	2019
Tang	Global Business Start-Up Award	IChemE	2019
Thielemans	Medical Imaging Technical Achievement Award	IEEE	2019
Andrews	William Froude Medal	Royal Institution of Naval Architects	2020
Colchester	Engineers Trust Young Engineer of Year	RAEng	2020