Institution: University of Leeds

Unit of Assessment: 11

1. Unit context and structure, research and impact strategy

Our research ranges from fundamental advances in algorithms and models of computation, through to highly applied research into new display technologies for clinical diagnosis, energy-efficient data centres, and profound insight into data across domains. We collaborate extensively with industry, have many joint projects with one of Europe's largest teaching hospitals(Leeds Teaching Hospitals Trust: LTHT), and have excellent connections with leading researchers and institutions worldwide(Figures-2/3). Our vision is to deliver sustainable, high-impact, long-term research excellence as demonstrated by outstanding outputs and the benefits which accrue to our disciplines, partners, industry, the local and wider economy, and society.

Our research continues to be organised using the five REF-2014 Themes which reflect our distinctive approaches to computational thinking: **Algorithms and Complexity**(AC), **Distributed Systems and Services**(DSS), **Artificial Intelligence**(AI), **Computational Science and Engineering**(CSE) and a "cross-cutting" theme: **Applied Computing in Biology, Medicine and Health**(BMH). Many staff are members of several themes(Figure-1). We have strong interdisciplinary links across the University(UoL), including strategic partnerships (e.g. LIDA(Leeds Institute for Data Analytics, lida.leeds.ac.uk, REF5a). The UoA aligns with the School of Computing(SoC) within the newly merged Faculty of Engineering and Physical Sciences. While finances are devolved to SoC, much of our administration and support is at Faculty level.

Research-related highlights include:

[H1] £96M new building(§4), realising REF14 plans for new research facilities and environment.

[H2] 30% journal articles in top 10% journal percentile(Scopus), greatly increased international collaboration (Figure-2); 1181 publications in institutional repository(322,600 downloads from 196 countries, averaging 176/working-day).

[H3] 2.4 best/runner-up paper awards per-annum and IEEE SciVis Test-of-Time award(§4).

[**H4]** Major expansion of **AI** (planned in REF-14) with six new staff(Figure-1), including three supporting growing robotics activity in SoC/across UoL.

[H5] CSE: commencement and subsequent renewal of EPSRC CDT (£8.34M, director:Jimack) on Fluid Dynamics(FD). *Petriva Ltd* spinout based on visualisation software for the petroleum industry. To support our vision, we have recruited in graphics (Kelly, H.Wang,+two arriving after 31/7/20) and in numerical computation (Lassila, Ranner). New international collaborations as subcontractor on US DOE/NNSA ECP Alpine Exascale Computing Project. **CSE/BMH**: Leeds Virtual Microscope(LVM) research led to REF3-UOA11-3. Qualdash software(NIHR-funded) deployed into five NHS hospitals' paediatric intensive-care/cardiology units.

[H6] DSS, appointment of two new Associate Professors(APs): Pournaras, Z.Wang). Two spinouts with £2M external investment: *Edgetic*, resulting from award-winning research in algorithms for efficient cloud computing; *Slingshot-Simulations*(digital-twin technologies), in collaboration with Jaguar-LandRover(JLR), EP/K014226/1.

[H7] BMH/AI: major new focus on AI and Health/Medicine: celebrated our 60th anniversary(2017) appointing a *Diamond Jubilee Chair*, Frangi and two supporting lecturers, creating a cross-faculty *Centre for Computational Imaging and Simulation Technologies in Biomedicine*(CISTIB), enhanced by Frangi's 10-year RAEng Chair in Emerging Technologies(CiET)(£2.68M); £5.9M UKRI AI+Medical-Diagnosis CDT

(Directors:Hogg/Dimitrova); lead partner with LTHT in Northern Pathology Imaging Collaborative(£17M).

[H8] AC: two new lecturers appointed(Figure-1) +1 in 2020-Q4; successful industrial trials on train-unit scheduling optimisation research(Kwan:EP/M007243/1), in collaboration with our spinout Tracsis Plc; the results are embedded in a commercial system used by >50% of UK train operating companies making significant savings from optimised schedules(REF3:UOA11-1). Publication of series of seminal papers, e.g. on (theta-wheel)-free graphs[REF2:UOA11-1133/4280], realising REF-14 plans to advance foundations of complexity and graph theory.

[H9] Active membership of the Alan Turing Institute(ATI): election of three SoC Fellows: Cohn, Ruddle, Hogg(also on *University Partners Board*).

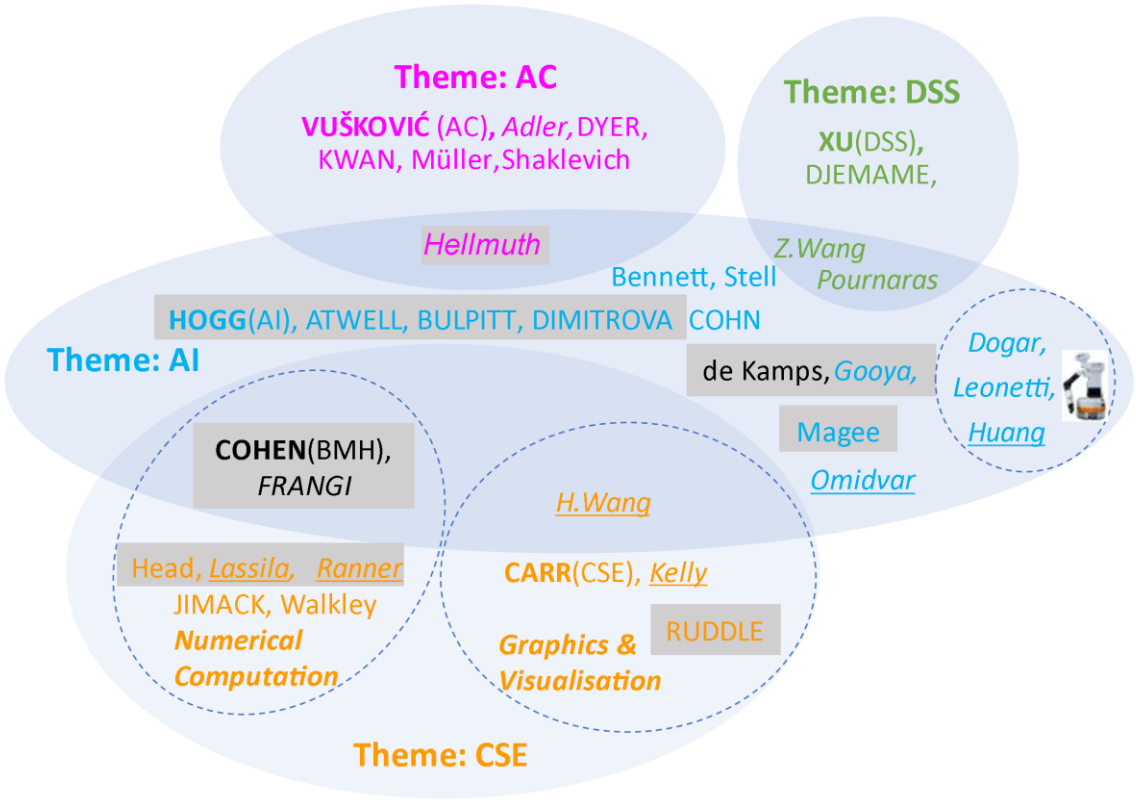

Figure-1. Theme members/overlaps.

Key: ECRs: underlined(6=17.5%)
Theme leaders: **emboldened**.
Professors(BULPITT & CARR promoted 10/ 2020): UPPERCASE.
Appointments since 2014(14=40.8%): *Italic*.
Text-colour indicates primary Theme membership(black=BMH).
BMH-Theme: Grey-highlighting.
Theme-subgroups: Dashed-ellipses.

We have implemented and surpassed our REF2014 plans (marked √ below)(see [H4,5,7,8] and Theme descriptions below), substantially enhancing our international standing, rising 37.5% from 24.9 to 34.25FTE and increased research income(§3). Accordingly, we have produced more higher-impact research within Theme, inter-Theme, and in collaboration with UoL/external partners.

AC-Theme

Vision: We use techniques from graph theory, logic, and operations research to address the theory/complexity of algorithms, including problems in scheduling and combinatorial

optimization. Our scope includes randomized and approximation algorithms, probabilistic algorithm analysis.

Highlights/REF-14 plan achievement: We have embarked on exciting new directions linking different domains within AC (e.g. Dyer/Muller:EP/S016562/1, bringing together two previously distinct areas: algorithms for random generation and approximate counting, and structural graph theory(√)[REF2:UOA11-96]) and across themes, e.g. AC/DSS: Shaklevich(EP/T01461X/1) connected scheduling and cloud computing((√) and industry(√)) building on her new exact world-leading algorithm for the important problem of energy optimisation in distributed systems, while Kwan has focussed on train scheduling(√)[H8,REF2:UOA11-63]. Our 2020 appointment Hellmuth brings powerful graph theoretic algorithms to bioinformatics with evolutionary insights[REF2: UOA11-4115].

Vušković gained new insights into hereditary graph classes, producing new structural results with important algorithmic consequences(√)(EP/K016423/1, EP/N019660/1)[H8,REF2:UOA11-1131/1132/1133/4280]. Adler's research combines logic and graph structure theory(√), e.g. to find the fastest known parametrised algorithm on planar graphs for the classical Disjoint-Paths Problem[REF2:UOA11-3343], and lower bounds for linkages, with applications in databases, machine learning, and sublinear time algorithms for querying big-data(√). Adler also leads a White-Rose funded collaboration with Sheffield/York "Foundations and Guarantees for Algorithms and AI", aiming to provide new algorithms for big data sets and networks that are extremely fast and come with accuracy and performance guarantees. PDRA Salfelder won Track-A(Tree-width) of the PACE-17(Parameterized Algorithms and Computational Experiments) challenge.

AI-Theme

***Vision*:** Six new staff[H4] support our broad vision to conduct fundamental and applied research spanning and integrating the modalities of language, vision, reasoning, learning, and robotics(√).

***Highlights/REF-14 plan achievement*:** We planned "to chart new territory integrating learning, reasoning, language, and personalisation … with insights from animal behaviour to deliver robust, adaptive autonomous systems"; we have made substantial progress on this(√)[e.g.: REF2:UOA11-4643/699/159/158/331/698/4688]. As well as continuing our fundamental research in and between AI modalities[e.g.:REF2:UOA11-4643], we continued to develop collaborations across UoL: health[H7], infrastructure engineering, Financial Technologies(Fintech)(Omidvar), science, environment/climate, humanities(further details below).

The growth of AI is strongly supported by two cross-University platforms: Robotics@Leeds(§3) and LIDA. Our ATI membership[H9] links us into a national AI community that greatly benefits our staff and PGRs alike.

Research on Decision Support Systems(D.S.S.)[REF2:UOA11-4644/4661] in the EU NetTUN project on Tunnelling(joint with SNCF) led to a ESWC-15 "best in-use" paper[journal version: REF2:UOA11-4644], and a keynote at the major tunnelling conference CTTU-20. The interdisciplinary Assessing-the-Underworld Project(EP/K021699/1), with major stakeholders in the sector (e.g. Balfour-Beatty/Costain) prototyped a D.S.S.[REF2:UOA11-4661] which has been well received in industry (new funding from Highways England) and runner-up best ISWC-16 resources paper.

Our research on robotics has grown(√)[H4,REF2:UOA11-3269/32673268/158/4088/4487/]: many new grants including two Marie-Skłodowska-Curie Incoming-Fellowships(Dogar & PDRA Figueredo), co-investigators(Cohen/Cohn) on the £4M EPSRC National Centre for Innovative Robotics, and two interdisciplinary EPSRC Programme grants(£4.3M-EP/N010523/1,£7.29M-EP/S016813/1) on infrastructure robotics; these build on Cohen's EPSRC Leadership Fellowship(EP/J004057/1) to study neural control behaviour(√)[REF2:UOA11-1406] whose models are now used on robots to find cracks in roads(BeCurious-2020: https://youtu.be/2avPQxqMC58, attracting industrial interest) and follow-on robotics project for pipe/sewer inspection(EP/S016813/1).

Six of the awards/prizes summarised in §4 reflect the quality of our robotics work, including those stemming from our involvement in the €8M STRANDS FP7-project focussing on long term autonomy in robots, where our results in activity recognition and grounding language to vision were an important part of this success(√)[REF2:UOA11-4643]. We are the only UK partner in the €20M AI4EU platform project, where we contribute to collaborative robotics research.

CSE-Theme

Vision: Our two-pronged mission is to advance the analysis/implementation of fast, efficient, correct, and reliable numerical algorithms for physical problems, simulation, graphics, rendering, animation and visualisation, while embedding fundamental developments in algorithms and cutting-edge computational techniques within end-user driven frameworks. A key part of our vision has been for our graphics group to take a leading position in the UK, underpinned by growth[H5](and new degrees in High-Performance Graphics/Games-Engineering).

Highlights/REF-14 plan achievement: Key pillars of our REF-14 strategy remain: extreme-scale computing (relying heavily on computational geometry/topology, Carr[H5,REF2:UOA11-2391/2390/2394/3603/3862/2392](√)); algorithms for modelling and simulation (especially computational FD(√)); and interdisciplinary collaboration(e.g., Ranner tackling free-boundary problems in biology(√)[UOA11-2951/2949,Leverhulme Fellowship(§4)]). New industry/external collaborations(ECP-Alpine (LANL/LBNL; UPMC-6 Paris; Kyushu/Riken, six Chinese Universities…) and applications within computer science and beyond, exemplified by collaborations with 10 Schools in our FD-CDT alone. New directions include integrating deep learning into computational frameworks in engineering(Jimack,doi.org/10.1007/978-3-030-50420-5_14, new monthly seminar-series), biology/medicine(Ranner/Cohen[EP/S01540X/1], Frangi[RAEng:CiET £2.68M).

Strong recruitment in both sub-groups(Figure-1)[H5] including Lassila(CISTIB, with FD expertise), Ranner(with fluid-structure interactions expertise), Kelly, H.Wang +2 appointments arriving after 31/7/20)(graphics) is bringing new opportunities in scientific computation, contributing to our interdisciplinary research in biology, medicine and surgical robotics (see BMH), and to graphics (e.g. our leading role in the development of the new University Centre for Immersive Technologies(CfIT; co-director:H.Wang) as well as in the Virtuocity centre(§3). In 2019, after 10 years as Faculty-Dean, Jimack brought renewed leadership. Ruddle was appointed as an ATI-Fellow and his visualisation work has led to commercialisation(√)[H5,REF3:UOA11-3,REF2:UOA11-315/11-1185].

DSS-Theme

Vision: Our mission is to investigate large-scale systems spanning communities, organisations, industries, and nations bringing together computational power, big data and human knowledge and thus to play a leading role in designing the next generation of systems and tools for: evaluating the performance of cloud services; flexible software abstractions; heterogeneous hardware platforms; massive-scale simulation; virtual systems engineering; data centre scheduling and analysis.

Highlights/REF-14 plan achievement: We achieved our 2014 plans to develop energy-efficient cloud data-centres(√)[REF2:UOA11-1588/1586/729/1585/1587/729/4063]: one unused ICS combines work in Djemame's ASCETiC project (being exploited by ATOS Spain and HP Italy) and Xu's *Edgetic* spinout; the TANGO project(EU:€3.1M) has taken this research forward, with the TANGO software toolkit, being exploited by Bull(France) and Deltatec(Belgium) and founding the Heterogeneous Hardware & Software Alliance(http://heterogeneityalliance.eu/). Our research into massive-scale distributed systems has broadened(EP/T01461X/1,£1M) with AC-Theme(Shaklevich), Alibaba, and Edgetic.

We planned major innovation in advanced systems engineering, which, through partnership with JLR(Xu-EP/K014226/1), has been realised in the *Slingshot* spinout(√)[H6].

BMH-Theme

Vision: BMH is a cross-cutting(Figure-1) interdisciplinary theme. Advances in computing are revolutionizing thinking, experimental set-ups and understanding across the life sciences as well

as in medicine and in healthcare domains. Our vision is to position ourselves as leaders of this revolution, across the BMH area.

Highlights/REF-14 plan achievement:

BMH has seen particular success[H7](√). Our 2014 plans to (i) develop systems and tools for biomedical data analysis[REF3:UOA11-3], (ii) deliver cutting edge computational models and algorithms (e.g. REF2:UOA11-3861/4623/3871/3872/3874/3873), (iii) grow collaboration across SoC, the NHS and industry (e.g. through CISTIB) have been dramatically exceeded(√): our long-term strong LTHT collaborations have allowed us to position ourselves at the forefront of computing applied to medicine/health[H7]. This investment in computational medicine, our leadership in LIDA(Ruddle:Research-Technology Director), growing links and leadership in the ATI and the new CDT[H7] will underpin our future growth.

SoC Research Plans

SoC's 5-year plans are to capitalize on our FTE growth, facilities/infrastructure and collaboration opportunities afforded by the new building's colocation with cognate schools(*§3*) to grow income and tackle major open and societal problems in our areas of strength. We plan strategic investment in staff across all Themes (with 1×AC, two 2×CSE, 2×AI/BMH faculty already advertised within the REF period). Through our new integrated robotics laboratory(*§3*) we will consolidate/grow our research in manipulation, bio-robotics, infrastructure applications, and learning. We will also embrace broader collaboration opportunities to address national/global challenges (in smart-cities/infrastructure, biomedicine, energy and climate change, robotics and fairness). We will work to deliver societal impact, e.g. through DSS research in energy efficiency, internet-of-things and smart-cities, robotics and AI for the built environment. Biomedicine/health will be a major focus, already supported by extensive funding[H7].

We aim to strengthen and broaden our existing external collaborations(Figure-3). A major focus will be to build on and benefit from our membership both the ATI and LIDA. We will continue our collaborations in infrastructure robotics, e.g. through a new Programme Grant(EP/S016813/1) joint with national/international/industrial partners. Spearheading UoL's internationalisation focus, we will consolidate and grow our extensive international collaborations(§4,Figure-3) with 11 live international grants(31/7/20).

Impact Strategy

SoC's impact strategy is overseen by its Research and Innovation(R&I) Committee(CRIC), and supported by the Faculty's team. We have continued to build on our previous strategy and success, using the Business Engagement Framework(REF5a) to support:

- Partnership with end-users: Our success builds both on long-standing relationships (e.g. LTHT) and on identifying and developing new relationships with industry (e.g. JLR), often via our many CDT partners. Our engagement with end-users is very broad, ranging from: hospitals (e.g. REF3:UOA11-3) and cardiac modelling, and in joint AI+Medical-Diagnosis CDT PhD projects; the utility/street-works sectors in the Pipebots project(EP/S016813/1,28 non-academic partners), Assessing-the-Underworld project(EP/K021699/1,57 partners) and a follow-on Highways England project, while REF3:UOA11-2 arose from the earlier EPSRC and InnovateUK Mapping-the-Underworld projects); the cloud-computing sector (Flexiant, Atos, Edgetic); the transport sector(REF3:UOA11-1), and an EU funded collaboration with French train operator SNCF on a tunnel maintenance D.S.S; the defence sector (e.g. DSTL CASE studentship). It ranges from start-ups, Vet-AI or pinpointdatascience.com (Hogg is on Scientific AB), to international names(e.g.:Burberry).

- Innovation driven research: We support staff in developing applied and translational research through funding of professional activities, strategic appointments, and mentoring for Fellowships (e.g. an RAEng Enterprise Fellowship for PDRA McKee(DSS), now CEO/CTO of Slingshot spinout). We support an agile approach to opportunities by actively seeking new partnerships and new application domains. These may arise from industrial stakeholder engagement events, or via direct contacts from industry in particular via our

commercialisation arm and the new Nexus facility(see §3/REF5a), e.g. VET-AI.

- Spin-outs, licensing, other commercialisation: Our track record in developing successful applications, from concept to product, is underpinned by cross-disciplinary collaborations and end-user input and evaluation, e.g. demonstrated by three new spin-outs(*Edgetic*, *Slingshot*, *Petriva)*, whilst we continue innovation with our earlier spin-out, Tracsis (REF3:UOA11-1). REF3:UOA11-3 arose from licensing of BMH/CSE research on the LVM. REF3:UOA11-2 stems from EPSRC/TSB/InnovateUK funded spatial data integration research leading to licensed adoption by the Scottish Road-Works Commissioner. We support knowledge transfer through memberships in external advisory-boards (e.g. Geospatial Commission NUAR: REF3:UOA11-2). We provide excellent training for a career in industry, with many now leading labs (e.g. PGR Alomari: Rolls-Royce).

- Impact through outreach/dissemination: We disseminate tools and research capabilities to the public, potential end-users, industry/government organisations, through publications, open-source software(§4) and licensing. See §4 for outreach activities.

Institutional facilities, expertise and resources support our impact strategy at every stage of the above pipeline. UoL's R&I Service provides a route for staff to undertake specific consultancy projects, with a share of the income made available to staff for funding personal development. UoL invested heavily in the Leeds Innovation Centre and its reincarnation as Nexus (£40M, see REF5a/§3); our *Tracsis* and *Slingshot* spinouts have offices in Nexus, and we collaborate with two other Nexus-companies: KTP with *VET-AI* exploiting our computer vision expertise; *Scaled Insights* who employed PGR Piotrkowicz. A Faculty-wide Innovation Hub serves as the point of contact for industry (offering business support, liaison services, knowledge transfer facilitation), and provides internal enterprise and organisational support for staff to apply their research and collaborate with industry. Successful applications to UoL's EPSRC Impact Acceleration Account have underpinned several of our impact activities(*Petriva*, REF3:UOA11-3, *Edgetic*, *Slingshot*, D.S.S. for streetworks).

Developing our strategy for impact: a culture in which staff view outreach, translation, and knowledge transfer as integral to research informs the strategic activities described above, our research and our training of future researchers. Support for the translation of our research through licensing and commercialisation activities involves a range of mechanisms and processes, from preliminary proof-of-concept funds, to advanced seed-corn funds, specialist input, business advice and more. We reward staff for their achievements through promotion(§2). Staff are encouraged to take courses on impact generation offered by the Organisational Development and Professional Learning(OD&PL) unit. Our Industrial Advisory Board helps inform and develop our strategy.

Promoting a culture of innovation and collaboration: We encourage staff/PGRs to take an active part in activities/networks that focus efforts around real-world problems and grand challenges. To grow the already substantial body of user-driven research, we run networking activities, including joint workshops with users, and mentoring, e.g. through alumni, UoL designated Business-Development Managers (one per priority area) provide dedicated support.

Focussed investment: We identified strategic priority areas – aligned with national/international challenges and EPSRC priorities – in which we have invested (via sabbaticals, appointments, large equipment(§3). These helped inform UoL priority areas for innovation (Stratified Medicine, Medical Technologies, Digital Technologies, Robotics, AI) that are earmarked for strategic investment. We will continue to incentivise impact generation (e.g. through reduced workload-allocation, seed-corn funding).

Impact Case Studies: REF3:UOA11-1 extends a 2014-ICS, *Tracsis*, which featured in the UKCRC/CPHC brochure on REF-2014 ICS, and is an AIM-listed spinout from the AC-theme, including both a spinout and licensed software as delivery mechanisms. The other two ICS rely primarily on software licensing:REF3:UOA11-3 arises out of BMH/CSE research, and REF3:UOA11-2 from AI – thus our three ICS arise from four themes, demonstrating the breadth of our approach to impact. Future ICS are already developing well in anticipation of the next REF, e.g. based on our *Edgetic*, *Slingshot*(both DSS) and *Petriva*(BMH) spinouts.

Approach to Interdisciplinary Research

Support of interdisciplinary research is a central pillar of SoC's strategy(~30% REF-2 flagged interdisciplinary). We have already noted our commitment to LIDA and both of our CDTs are highly interdisciplinary: all new students have a second supervisor (in Medicine for the AI+Medical-Diagnosis CDT and across 10 other Schools for the FD-CDT). The Theme descriptions give examples of interdisciplinary strengths. During the REF period 62% of our PhDs have been joint with another School, actively directing studentships to facilitate this. We have encouraged and targeted interdisciplinary funding sources, having received funding from **all 10 UKRI councils** as well as the NIHR, Nuffield, Welcome, CRUK, Kidney Research UK, LTHT, MOD, British-Academy, Royal-Society and RAEng. We appointed Frangi 60%-40% with Medicine to help grow our health research, as well as seconding Dimitrova 50% for two years. Ruddle is 20% seconded to LIDA. We have invested in facilities (e.g. "Wormery"(§3) which has facilitated interdisciplinary research with biology/physics(e.g. https://doi.org/10.1007/s10404-020-02362-2). Our advertising for new faculty explicitly states interdisciplinary research as a desirable attribute.

In **Fintech**, we are a key contributor to UoL's strategic focus in this sector, bringing us together with researchers in Business, Mathematics, Law and Applied Ethics. There is growing collaboration with organisations such as Barclays and Ernst&Young, centred on the transformative potential for AI within financial services, supported by Visiting Professors[1]. We created a new 50%-50% UAF[2] position with the Business School(Omidvar, winner of EEE CEC-2019 large-scale global optimization competition) to help grow this area.

In **Science, Engineering and Humanities** research, we are exploring the potential for machine learning across all disciplines. The momentum behind the adoption of AI across Leeds has resulted in new research collaborations, projects, and proposals in many areas, including Mechanical Engineering, Geophysics, Atmospheric Sciences, Psychology, Medicine, Philosophy, Transport Studies and Geography. In the Digital Humanities, Stell co-led an AHRC network(AH/R006482/1) *Space and Narrative in the Digital Humanities*, joint with History at Lancaster and the POLIS centre(Indianapolis), exploring how Qualitative Spatial Representations (a research area SoC co-founded), can be used to help analyse texts where spatial information is vague/imprecise/missing/ambiguous.

There are regular joint seminars with other Schools/Centres/Institutes (e.g. LIDA, Maths, Languages Cultures and Societies, robotics). SoC actively participates in/co-leads a variety of joint Centres, e.g. Robotics@Leeds (robotics.leeds.ac.uk), Virtuocity (https://lida.leeds.ac.uk/research-projects/virtuocity/), LIDA, CfIT. External interdisciplinary collaborations are common, see examples above.

Progress towards an Open research environment

SoC adopted a robust approach to open research in 3/2014, following the REF-2021 Open-Access(OA) policy announcement. Going beyond these requirements, from this date authors were required to deposit all outcomes (not just anticipated "REF papers"), ahead of the mandatory deadline. Quarterly monitoring facilitates compliance, with one-to-one support available.

This approach has led to >90% of papers published since 3/2014 deposited in our Institutional Repository(total:1161 up from 260 on 31/7/13), with >322,600 downloads(from 196 countries) from the repository, i.e. >126/day. All REF-submitted outputs, and published while an author was employed at Leeds, are available openly except where a publisher's policy intervenes. We have made 134 articles available via Gold-access, and 98 Bronze-access.

SoC had 219 PhD theses in the White Rose repository on 31/7/2020(81% increase since1/1/2014) with >129,000 downloads(~1760/working-day).

[1] Chris Sier: Fintech Envoy for HM Treasury/Chairman of Fintech North. Adam Beaumont, CEO of telecommunications provider aql, Visiting Professor of cyber security@UoL. Matthew Gould: CEO for NHSX, Government Director-General for Digital and Media Policy until 2019.
[2] **U**niversity **A**cademic **F**ellow – see REF5a.

UoL implemented its Research Data Management Policy in 2017 though many SoC researchers had already been sharing data and code, thus complying with funder policies and ensuring it can be shared, reused and cited beyond the project end. Data is archived either in the Institutional Data Repository, with DOIs(26 datasets in period, with 2178 page-views and 1373 downloads since analytics started on 1/1/2019) or elsewhere. Open repositories of code are the norm. ORCiDs are required for all, ensuring our work is clearly identified by individual/organisation.

Research Integrity:

We uphold the principles in the concordat to support research integrity, which are embedded in staff inductions, and reinforced/refreshed through staff meetings, CRIC, and in SRDS/AAM(§2). Principles in the EPSRC's Framework for Responsible Innovation are taught to PGRs and embedded into training programmes associated with large projects. Our academics play a leading role in promoting ethical innovation(e.g. Pournaras leads the White-Rose project *Socially Responsible AI for Distributed Autonomous Systems*).

Staff with managerial responsibilities undertake appropriate training led by the OD&PL unit, and must follow UoL's leadership excellence behaviours(REF5a).

Our formal OA and Research Data Management policies support transparency in the open sharing of research results and research data, which themselves comply with the requirements of major research funders and best practice.

A Faculty ethics committee provides guidance, audits compliance, and appraises proposals with significant ethical dimensions. Research grants/contracts make a risk review declaration before submission, including ethics appraisal, safety, data management, anti-bribery, export control legislation, and potential conflicts of interest. For PGRs this forms part of their annual review.

We uphold professional standards by encouraging (and financially supporting) obtaining and maintaining professional membership and CEng/CITP/Fellow status(§4).

2. People

Investment in individuals and supporting activities is an essential part of delivering our vision. Early in the period we developed a plan for significant growth to encompass staff at all levels. Of the staff returned, 14FTE are new(40.8%): 11 Lecturer/UAF, 2 AP, and the Diamond Jubilee chair[H7](dowry £111.4K + 2xLecturer + 3PGR). Following our 2014 plans, we identified key areas to bid for University-supported UAFs to: Robotics(Dogar, Huang), DSS(Townend), and in 9/2019, FinTech/AI(Omidvar); Dogar and Townend's research progressed so well that Dogar passed probation 2 years early, while Townend became CTO of our Edgetic spinout. We supported Leng in her successful bid for an EPSRC Research Software Engineer(RSE) Fellowship, Ranner for his Leverhulme Fellowship and both Marie-Skłodowska-Curie Fellows(§4). To protect our research (that helps draw students to Leeds), we also made two strategic appointments of new lecturers to support our large educational offer and growing class sizes.

Recruitment always aims to recruit the very best we can, from broad backgrounds, across areas where possible, and re-advertising if necessary. Targeted recruitment (into specific areas) takes into account critical mass and strategic objectives; e.g. following Lau's retirement and Townend's move to Edgetic, we advertised specifically to recruit into DSS[H6]. Other strategic appointments during the REF period to strengthen our existing research themes are: CSE in graphics (H.Wang, Kelly) scientific computation(Ranner); AC(Adler, Hellmuth); AI(Leonetti, Dogar, Huang). All academic staff are appointed to open-ended contracts.

We implement the *Concordat to Support the Career Development of Researchers,* in line with UoL's Employment Policy(REF5a). We support career development through: an Annual Academic Meeting(AAM) and access to funded staff development. AAMs identify academic and developmental needs, mechanisms for support and opportunities to adjust workload, e.g. increasing buy-out to provide time to lead a substantial research/admin activity. In addition, longer-term career plans, promotion and development are reviewed in individual annual Staff

Review and Development meetings(SRDS). Outside of annual meetings, regular reviews with mentors and SoC's Director of R&I(DoRI) allow staff to discuss research progress and plans. Heads of Research Theme support staff both individually and in Theme meetings and "away days".

Promotions are by self-application, with no University-imposed financial constraints; all staff are encouraged to apply for promotion and are mentored individually and at Faculty workshops which include previously successful SoC applicants. Seven staff have achieved professorial promotions(bringing our female professoriate to 21%, and two disabled), and four to AP. Senior staff annually consider recommendations for accelerated and discretionary increments as well as those from self-application.

Support for ECRs, including PDRAs

Themes aim to provide a critical mass of staff and shared research infrastructure that delivers support that particularly benefits individuals at the start of their careers and helps them integrate into the research culture. They provide: a forum for interaction between staff at different career stages; researcher collaboration; support for grant and fellowship applications including peer review. Seminar series, at Theme and School level, delivered by national and international speakers (continued remotely during Covid-19), cover a wide range of contemporary topics and help staff/PGRs develop contacts.

Individuals at the start of their careers are helped with reduced teaching/administration duties (UAFs normally have no modules until year 4) and receive a customised start-up package including travel & at least one studentship. The package may include capital support(§3). We attract, support and retain researchers by providing: dedicated research labs with specialised equipment, particularly for Robotics and Graphics/Visualisation; ongoing contributions to their staff account coming from an allocated percentage of the gross amount of research income; funding for attendance at conferences and visiting academic/industrial partners as required; and, support/funding in patenting and commercialising research.

Every ECR (including PDRAs) has a probationary supervisor, and separate mentor. Theme leaders take an active role in mentoring and supporting ECRs and PGRs. The annual AAM/SRDS identify and agree needs, goals, support, and methods to achieve ambitions for all staff, but are particularly valuable to ECRs, as are the probation meetings for new recruits. ECRs particularly benefit from UoL's training and development opportunities led by the OD&PL, Research & Innovation Service (RIS) and the Library, and include targeted support for grant/fellowship applications, interview practice, and research impact. ECR networks provide opportunities to share experience/best practice, and to have a combined voice. We have had continuous ECR representation on: Robotics@Leeds Executive Committee(Dogar, Leonetti); CfIT(H.Wang); CRIC and the Faculty R&I Committee include an ECR. Two SoC PDRAs are on the Faculty Equality and Inclusion(E&I) committee.

We develop individual career paths for our PDRAs through regular academic/pastoral meetings, and via training/development activities. University, Faculty and School international mobility funds, introduced in 2019, allow PDRAs/ECRs to apply independently to attend conferences and for collaborative visits. They are encouraged to take responsibility for various aspects of our research environment (e.g. helping to manage lab facilities; organisation of seminars, student mentoring, helping to write grant proposals, as well as teaching). We encourage and support PDRAs to obtain their own grants/fellowships (e.g. McKee: RAEng Entrepreneurship Fellowship; Figueredo: Marie-Skłodowska-Curie Fellowship). Our PDRAs predominantly go onto further PDRA positions, Tenure-track academic positions, or industrial research labs(e.g. Garraghan: Lecturer@Lancaster; Clement: Technical lead of *Edgetic*).

PDRAs are supported by their academic mentor/probation advisor and HoS to achieve their academic targets and develop independence. Support in applying for, and securing, fellowships is provided (see above), and we mentor PDRAs to be named as a researcher co-investigator on applications(e.g. McInerney on NIHR129483). We organise specific events e.g. a 1-day White-

Rose" Symposium for early career researchers", including discussion on how to shape your research and 1-1 mentoring academic-PGR/PDRA.

A formal HR meeting six months before the end of each PDRA's contract explores future opportunities (including priority for positions in UoL via the redeployment register), and to give the candidate good notice. Bridging funding is available when appropriate.

This support and integration is evidenced by ECR retention: only two tenure-track ECRs have resigned since 1/1/14: Townend to co-found the *Edgetic* spinout, and Shao who returned to his native country for personal reasons.

Sabbatical policy

Our sabbatical policy is intended to support research and provide the seed for larger, longer-term collaborations with major impact. E.g. Carr's 2015 sabbatical at Los Alamos(LANL) and Lawrence Berkeley National Laboratories (LBNL), which not only supported an existing collaboration with LBNL, but also sparked Carr's involvement in the US Exascale Computing Project(ECP-Alpine), including developing and delivering nearly 10% of the next-generation vtk-m visualisation toolkit(REF2:UOA11-2391), and already running on Summit (the world's #2 supercomputer).

Applications can be flexible (e.g. whole year vs one semester; or specific teaching/admin duties relief). Moreover, our workload model aims to keep teaching loads low for research active staff, normally 2x10/15 credit modules per-annum, with relief for major administrative duties, and 5% for service activities. All applications are considered equally, according to the same criteria (benefit for the individual and SoC), irrespective of contract status. We try to take account of staff preferences in the timetable regarding scheduling their teaching so as to maximise effective research time (e.g. all teaching in one semester, or on particular days of the week, or to teach our short block 2 week modules in our joint School in China(REF5a)).

Stimulating and facilitating exchanges with industry etc.

SoC encourages links and an active dialogue between staff and third-party organisations, including industry, and the health sector. We have Visiting Professors (e.g. Davies from BAES and footnote-1) and RFs from industry who interact with staff and give seminars. We supported PDRA McKee to gain an RAEng Entrepreneurship Fellowship who has subsequently helped spin out a company (*Slingshot Simulation*, joint with Xu). We have actively sought to recruit staff with industrial experience (e.g. H.Wang from Disney Labs in Los Angles, Kelly(Strobee startup and ESRI). We aim to maintain contact with staff who have moved on to the industrial sector, e.g. by inviting them back for one-off events/appointing them to our industrial advisory board. Most of our research grants have at least one industrial/third sector partner and these provide very useful two-way exchanges. We actively seek to co-create research grant proposals with industry(e.g. EP/N010523/1, EP/R031193/1, EP/S016813/1, EP/T01461X/1).

Supporting Impact generation and rewarding staff

We reward staff for their achievements: through promotion for innovation and impact(Ruddle, Kwan promoted to Professor), allocated workload (e.g. Cohn, Kwan, Ruddle, Xu), sabbaticals and salary increments. The Faculty's R&I Service offers staff tailored advice and help with impact, from initial proposals, through to negotiating contracts, NDAs and attracting VC: indeed impact such as *Petriva*, *Slingshot* and *Edgetic* would not have come to fruition without this. The AAM discusses opportunities for impact development and what School resources would help in achieving this. SRDS meetings discuss aims in impact development and how they can be supported.

PGRs

Our PGR numbers have nearly quadrupled: at 31/7/20 there were 210 PGRs(129.21FTE), up from 45(32.95FTE) registered on 31/7/13, with 51.5% female registrations over the period). As the CDT cohorts finish, this will yield greatly increased graduations.

PGR recruitment is administered by the Faculty Graduate Office, which ensures a consistent process and fair assessment of applications. We host open-days and recruitment events staffed by existing PGRs, and advertise on e.g. www.findaphd.com, subject specific email lists, and through alumni networks. Prospective PGRs are invited to see facilities and discuss aspirations, and candidates are interviewed by a panel including at least one independent.

For each of our CDTs, we offer places to those who demonstrate the strongest aptitude and enthusiasm for the CDT approach: the desire to engage actively as part of the cohort, and a commitment to the professional development components of the programme. Where applicants are similar in terms of aptitude and enthusiasm, a secondary consideration comes is to ensure a balanced cohort in terms of academic background and diversity. In the FD-CDT, a twin-track process recruits 30% to work specifically with an external partner, with the rest on an open-track will later choose their projects from those proposed by academics, or industry-sponsored.

Successful candidates are supported with the registration process, and for international applicants, with visa procedures. Many PGRs are recruited from our undergraduate/MSc base, encouraged by our policy to embed project work in research laboratories and to provide competitive 8-week (or longer) summer laboratory placements (School funded, or via the EPSRC vacation bursary), though most are externally recruited from around the world, based on excellence.

Our students are supported by a number of funding sources: (i) CDTs (ii) EPSRC DTP/DTG scholarships. (iii) other grants, e.g. EU projects. (iv) Case-Studentships(e.g. DSTL). (v) Overseas governments(37 in period). (vi) A School Scholarship fund (24 full and 8 partial studentships, £2.2M over the period). (vii) UoL scholarships(11). (viii) HDRUK MRes Programme(6 studentships). (ix) Studentships from other funders (e.g. NERC, ESRC, MRC, BBSRC, NC3R). SoC-controlled Studentships are used to: support PGR training in core research areas and areas that we aim to grow, as well as: complementing EPSRC Programme/Prosperity Partnership/Platform grants; supporting newly-appointed staff and in particular ECRs and, co-funding studentships with industry and international scholarship schemes. The availability of external funding does not affect our quality decisions on whether to make an academic offer to a student or not. PGR recruitment is managed by a PGR recruitment tutor, overseen by the DoRI. Students are supported to attend conferences, workshops and summer-schools (£120.6k from SoC + funds from CDTs and research grants).

Monitoring and support mechanisms for PGRs

New PGRs have a second supervisor to provide extra support and stability. There is a developmental review after four months, with formal transfer from provisional to full registration by month 11. Developmental reviews follow in subsequent years. All supervisors check and provide feedback on mandatory recording of supervision meetings on the GRAD system (also checked by the PGR tutor/Graduate Office). Students agree a training plan within their first three months, which is then monitored. For those PGRs only having three years of scholarship, SoC will normally provide at least a further 6 months of funding, subject to satisfactory progress. We encourage PGRs to contribute to our teaching programme (for payment) and to register for Associate HEA Membership. Staff new to supervision attend a University training course and receive mentorship from a senior co-supervisor.

A student having problems can see their supervisors, other Theme members, PGR tutor or DoRI for help (with extra support/flexibility available since Covid-19). This may be supplemented by procedural advice from the faculty administrative team. The Leeds Doctoral College brings together the support services available, including Faculty graduate schools, training, the Library, the Language Centre, IT, the Students' Union, research showcases, and talks on mental health, well-being and career development.

PGRs are fully integrated into the life of the School and are treated as staff for most purposes. PGRs are represented on CRIC, and play a leading role in the PGR forum which manages day-to-day PGR matters. Monthly Forum meetings discuss PGR procedures, disseminate information about changes in procedures or policies and identify problems. The forums are often followed by SoC-sponsored social events. PGRs can ask for a subsidy for any other events that

they want to organise among themselves.

Students are expected to attend the main seminars of their research group and to give Theme/School seminars during their PhD, with feedback from peers/staff. An annual PGR symposium is organised by the PGRs themselves with guidance from the PGR tutor. PGRs are encouraged to participate in Faculty/University PGR events, and have won prizes at these.

UoL conducts biennial postgraduate experience surveys(PRES). SoC has averaged 91% agreement to the question "Overall, I am satisfied with the experience of my research degree programme" in the REF period. PGR destinations are principally further academic positions and industrial research labs. PGR Chew, now PDRA at CMU) obtained an EPSRC prize Scholarship.

Equality and Inclusion/Diversity(E&I)

We follow and play a leading role in formulating UoL's E&I framework (Dimitrova is Faculty E&I lead) ensuring that colleagues are treated dignity and respect, opportunities are open to all, and everyone enjoys a safe, supportive and welcoming environment. We use Athena SWAN as a catalyst to develop and deliver a sustained E&I agenda targeting protected characteristics, supported by a diverse E&I action group(PGR+6 staff). The Engineering Faculty (including SoC) earned Silver (2015 and 2019, the latter led by Dimitrova). SoC's E&I lead(Cohen) sits on the School Management Team, and E&I is a standard item on SoC committees. We run regular themed activities (Ada Lovelace, Black History Month, disability related to embed diversity and E&I values into our culture and research (e.g. fairness in AI themed panel for the latest Black History Month event), and participation in EPSRC Inclusion Matters Project(https://northernpowerinclusion.org/). We consider E&I when nominating speakers for seminars/colloquia, awards/prizes, internships, and fellowships.

We aim to ensure that our recruitment and promotion is unbiased, and special circumstances are taking into consideration (e.g. career break, disability) with, e.g. compulsory E&I training for interview and promotion panel members, and a gender balance on panels. Our staff originate from 17 different countries/5 continents. Career breaks are explicitly accounted for in promotions, and promotion criteria have been updated in this period to include recognition of outreach, E&I activities, and mentoring/supporting colleagues. Promotion workshops were held to encourage staff from diverse backgrounds, inviting role models who provide mentoring and peer support. Our online *Staff Footsteps* booklet offers inspirational stories by people from under-represented groups and different career stages.

We enable flexible working to support staff with caring responsibilities or ill health, including 'keeping in touch' days, working from home (even before Covid-19), or via a longer-term contractual change. We provide support to those returning from a significant period of leave (maternity/parental, illness), and for those with caring responsibilities, including financial support to attend conferences/training courses, priority for PhD studentships, and reduced teaching workload. Our Faculty review on how Covid-19 could impact staff fed into UoL's HR policies review.

We work closely with OD&PL regarding the Researcher Concordat(REF5a) and helped pioneer the establishment of an ECR Faculty forum. The Faculty developed the Career Architect scheme to support PDRA career development into both academia and industry; this is now adopted across UoL. The *Women Rising* programme (initially funded by EPSRC, now by the Faculty) supports ECRs and covers a range of academic skills, e.g. grant/fellowship writing, networking, presentation, and tackling lack of confidence and 'imposter syndrome'; these programmes target researchers who are most likely to be on fixed-term contracts. The *Aurora* scheme is an important national leadership development vehicle for mid-career women in STEM. Our redeployment scheme is equally effective for women and men.

We organise staff support groups around protected characteristics, offering opportunities for networking and peer support, and our *Breaking Boundaries in STEM* events (e.g. our annual *LGBT+ Research Day*, *Ada Lovelace day, Black History Month, UK Disability History Month*) provide vehicles to promote, and discuss issues affecting such groups and include role models from academia and industry. Our *Mutual Respect* campaign addresses harassment and

inappropriate behaviour. Wellbeing workshops on resilience and mindfulness, organised for our faculties and open to all, are delivered by UoL's counselling team.

The Faculty aspires to be a regional hub for inclusive R&I. As part of the EPSRC inclusion project 'Northern Power', we lead activities to attract, grow and retain researchers from underrepresented groups in the North. Our joint activities with industry, e.g. 'Building Equality' and Leeds LGBT+ Pride, panel on visibility and BAME with representatives from KPMG and NAG, challenge societal perceptions of diversity in engineering and provide role models. A strategic STEM outreach approach is developed, targeting of students from underrepresented groups (e.g. BAME, LPN, GRT, BTEC, Care-leavers) from our partner schools and colleges. Our research staff and students engage in school days, campus visits, summer schools, and public outreach events (e.g. 'Be Curious', Leeds Digital Festival) to help encourage interest in STEM. We are expanding geographical reach of STEM engagement with schools across the country via digital activities and resources.

E&I with regard to the REF submission

The Unit's REF preparations, and those involved in the preparation of this submission, have been undertaken in accordance with UoL's REF2021 Code of Practice. All staff undertake E&I training, and all individuals involved in the REF2021 decision making process are required to undertake additional training. Equality impact assessments were undertaken to ensure due regard to equality issues occurred throughout the REF submission process and final decisions were made with a multi-gender team including the E&I lead. These have allowed us to: understand the representation of the eligible and submitted staff against our staff profile; understand how the selection of outputs for submission represent the diversity of staff; and, identify where progress on diversity issues is needed so that this can be strengthened in the delivery of the Unit's and UoL's R&I strategy.

3. Income, infrastructure and facilities

The School has increased its research income in the current REF period compared to the previous period: 81.25% total increase, and 29.46% increase of the yearly average income. We have obtained funding from **all 10 UKRI councils** as well as the NIHR, Nuffield, Welcome, Leverhulme, NC3R, CRUK, Kidney Research UK, LTHT, MOD, British-Academy, Royal-Society and RAEng.

Highlights of our income include:

- RAEng Chair in Emerging Technology £2.7m(Frangi)
- Co-investigators in new Programme/Grand-Challenge Grants totalling £11.5m
- Participation in 17 new EU grants totalling £6.34m for Leeds.
- Northern Pathology Imaging Collaborative(£17M) plus CDTs(£14.24M) [not REF-able income]

Acquiring research funding is a key strategic objective and is supported and monitored by CRIC and the Faculty's R&I Committee. Staff are individually supported by peer mentoring, Theme meetings/activities, and AAM/SRDS discussions. The DoRI and their deputy provide support and advice, and flag up funding opportunities. Candidates for competitive research fellowships at all levels are identified and mentored by SoC and Faculty. Practice interviews help prepare candidates for formal interviews. SoC provides matched funding to support research grant applications, from PGR studentships, teaching relief, equipment purchase/maintenance to support posts and additional travel budgets. As a result, 93% of submitted staff have Leeds-reported research income in Leeds (5 recent arrivals after June 2019, and two ECRs excepted). Staff receive a percentage of the project budget into their staff fund to support their research (total expenditure: £318.5k) giving freedom to undertake ad-hoc and seed-corn/proof-of-concept activities easily.

Organisational infrastructure supporting research and impact

Within SoC, the Theme Leaders and DoRI facilitate, encourage and support research and impact, strategically and day-to-day. SoC participates in, and helps lead a number of cross-faculty/interdisciplinary structures which facilitate our research: (1) Robotics@Leeds

(robotics.leeds.ac.uk) – which brings together all robotics research across UoL, has regular seminars, and houses the EPSRC National Facility for Innovative Robotic Systems(Co-Is Cohen/Cohn) with specialist machinery for constructing purpose-built robots. (2) Virtuocity (uolds.leeds.ac.uk/facility/Virtuocity) which aims to help communities and businesses to design the city of the future (see below), which is part of CfIT, an interdisciplinary collaboration which works with partners from the public and private sectors to drive innovation, using virtual and augmented reality. (3) The Leeds Institute for Fluid Dynamics. (4) LIDA through which are membership and activities in the ATI are channelled. LIDA opened in 2015, occupies 1583m^2, and provides Safe Rooms for research with identifiable personal data, NHS DSPT/ISO27001 IT infrastructure for research with identifiable and pseudonymised personal data, and a multidisciplinary research environment for 156 people. UoL has made ongoing investments totalling £2.9m to make LIDA's facilities free at the point of use, with SoC participating in £10.5M externally funded interdisciplinary projects. SoC is LIDA's third largest inhabitant, including our AI+Medical-Diagnosis CDT students who benefit from the proximity to the many other LIDA health researchers.

Operational and scholarly infrastructure supporting research and impact

A £96M investment to construct the Sir William Henry Bragg Building (delayed by Covid-19) completed in 2021 Q1 to house SoC and Physics, as well as a faculty-wide Integrated Robotics Lab which will help foster interdisciplinary robotics research; this will contain the School's existing robots (see below) as well as two Frank arms for Huang(£33k) and two Da-Vinci surgical robots, and a number of rehabilitation robotic devices. It contains purpose designed and built laboratories for each of our research activities. This facility will provide, for the first time in SoC's history, a building *designed* to meet all our needs, and will provide a step change in our research environment and ability to conduct leading edge research. It will integrate us much more closely into the newly constituted Faculty of Physical Sciences and Engineering (all eight Schools except Maths now being co-located.

SoC has made substantial investments in infrastructure and equipment. A new robotics lab was created(2015), now housing a Baxter(~£30k), a TiaGo(~£50k for Leonetti), a UR5 arm on a Clearpath omnidirectional base, with motion-capture infrastructure(£129.3k for Dogar), a Scitos A5, servers, as well as a fleet of Turtlebots for student research projects. A new AI research lab has been created to house our growing community of AI PGRs and PDRAs. A motion capture system lab(£178.4k) to support H.Wang's research was constructed. The "Wormery" supporting Cohen's C.elegans research has seen >£40k new equipment. Laboratory refurbishment (excluding the new building) has totalled £101,500.

Staff and PGRs have: modern twin display desktops, supported by servers in the lab and GPU compute clusters as necessary; free access to UoL's regularly updated HPC facilities, including GPU clusters(arc.leeds.ac.uk). Support and training is available for use of these facilities, including a team of RSEs, directed by UoL's Research IT manager, with one (EPSRC-Fellow Leng) embedded within SoC, as well as two further project-funded RSEs. Day-to-day IT support is provided by central IT, usually by staff embedded within the building.

E&I Issues

RIS provide active support including training, networking, financial/contracts support, assistance with impact plans and coordination of large proposals. Recent Faculty training workshops involved 40% female attendees. Researchers are encouraged and supported in applying for research grants. Unsuccessful applicants are offered additional mentoring. Positive impact of our research grant application support is evidenced with female successes: similar % male and female awarded grants, women associated with 24% of the total value of funding in Faculty (despite the eligible pool of females who could be named on a grant application being between 17.3%-20.1%); women are more likely to bring in funding as Principal Investigator.

Researchers are supported in preparing successful grant applications by their Themes, SoC, the Faculty Research and Innovation Committee, and by RIS. We enable flexible working to support staff with caring responsibilities or ill health, including working from home(even before Covid-19), to enable research grant preparation *inter alia*. We support those returning from a significant period of leave (maternity/parental/illness), and for those with caring responsibilities, via a

reduced teaching workload and financial support to visit collaborators or attend conferences/workshops, as well as funding for an accompanying partner, and via priority for PhD studentships to help pump-prime research proposals. Offices and laboratories are adapted for those using wheelchairs or with other specialist needs(£131k in period).

Use of infrastructure, facilities and expertise in relation to impact activities

SoC/LIDA/UoL computational and other facilities are available to staff to engage in impact activities, and we may second staff out to industry (e.g. Kwan to Tracsis). PDRA McKee was mentored for RAEng Entrepreneurship fellowship leading to the *Slingshot* spinout. PDRA Garraghan developed new test cases for evaluating fault-tolerance of production computing systems for Alibaba Group. RIS and Nexus provide ongoing support and facilities in this regard(REF5a).

Specialist infrastructure

Already mentioned above is the extensive investment in LIDA (£2.9m); additionally UoL has committed £1.2m to design and implement a new cloud-based NHS DSPT/ISO27001-accredited platform for the coming decade. UoL has invested heavily in its ARC HPC mentioned above, in accordance with a longstanding strategy of biennial hardware upgrades (most recently £2M in 2019) and maintaining a specialist support team. Since 2019 this has been supplemented through recruitment of a new RSE team. Together these support research throughout this Unit, including FD, and in particular, AI. Since joining the ATI, we have been making use of their HPC facilities and the N8 HPC facilities, based at Leeds until 2018. Hogg is also co-I on Jade2(EP/T022205/1), providing another source of HPC.

We setup a cloud computing testbed (16-node cluster, £60k) to support our research on Quality of Service in cloud virtualised infrastructures which has seen heavy use since then, including in our research-led teaching in the area.

Virtuocity is a UoL unique, immersive, human-in-the-loop simulation and visualization facility(£2M+) for city simulation and co-design powered by academic models and industry software, comprising three simulation laboratories: Driving Simulator; Truck-SIM; HIKER(Highly Immersive Kinematic Experimental Research laboratory), the world's largest 4K resolution 'CAVE-based' pedestrian simulation environment including the UK's only Omnifinity Deck, one of the most advanced omnidirectional treadmills in the world, to run experiments that allow participants to explore large-scale virtual environments(EP/R008833/1, CoIs: Hogg, Ruddle). Experiments can look at the impacts of a wide range of human factors including age, vision and mobility, e.g. in https://vericav-project.co.uk(InnovateUK).

The EPSRC co-funded National Centre for Innovative Robotics based at Leeds(£4M,CoIs: Cohen/Cohn) provides many specialist facilities, including advanced manufacturing/tooling (https://robotics.leeds.ac.uk/facilities/manufacturing-assets/), e.g. an Objet1000 Multi-Material 3D Printer (Stratasys) (0.4m^3 build area) which can combine multiple build materials from soft silicone-like elastomers to rigid nylon-like plastics. We have used these facilities in a range of robotics projects in SoC, as well as in our C.elegans Wormery.

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

Arrangements and support for research collaborations,

SoC, Faculty and UoL strongly support collaborative research, both internally, and externally, whether with other academic institutions, both at home and abroad. E.g. Frangi and Omidvar are joint appointments (Medicine, Business respectively) and Taylor in Mechanical Engineering joined UoL as part of Frangi's team and has a SoC office. Most of our projects are collaborative. We support large collaborative grants with SoC-funded studentships(e.g. EP/S016813/1). Examples of international collaboration include Vuskovic's with Princeton and ENS Lyon, Carr's with the OE/NNSA ECP Exascale project, along with 15 multisite-EU projects.

UoL strongly supports international collaborations, with a Deputy-VC(International), Faculty Pro-Deans(International) and School Internationalisation co-ordinators, each with funds to help colleagues initiate or maintain international collaborations; e.g. seed-corn funding for Gooya

allowed him to successfully apply for a JSPS Invitational Fellowship for Research in Japan, while seed-corn funding for Head facilitated a visit to Eindhoven resulting in Physical Review Letters(2019) paper. RIS, the Deputy-VC(International) and Faculty Pro-Dean(International) help develop new partnerships and maintain existing ones, and RIS provides logistical support in collaborative research grant preparation. All staff can use their staff account to initiate/maintain collaborations easily without needing to request travel funds. UoL's European Office offers matching funds for EU grant preparation. We have collaborated with many international academic partners in EU and other funded projects, with a steadily rising percentage of papers published with international co-authors(Figure-2). We have lead/co-lead research networks (e.g. SandH, an interdisciplinary network joint with Lancaster and Indianapolis(AH/R006482/1,Stell)). Figure-3 below demonstrates the breadth and extent of our University, national and international collaborations.

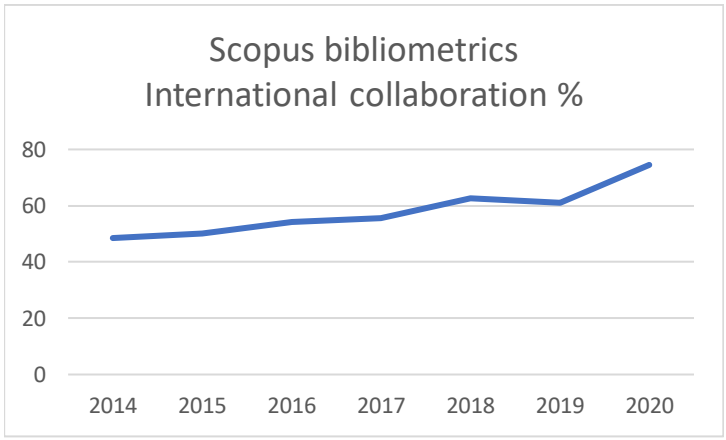

Figure-2

Relationships with key research users, beneficiaries or audiences to develop impact and how these collaborations have enriched the research environment

We have extensive collaborations with non-academic institutions across the UK and the world(Figure-3), and >6% of our publications have an non-academic co-author(Scopus). Many of these have led to research impact. E.g. our line of research in collaboration with utility companies started in 2004 and has continued to flourish, broadening into the Built Environment sector more generally; e.g. the Assessing-the-Underworld(ATU) EPSRC project(EP/K021699/1) had 57 non-University partners, building on prior Mapping-the-Underworld(MTU)-project. Leeds built a prototype D.S.S. as a major output from the project which was well received by our partners, leading to an EPSRC IAA, and Highways England funding. As a result of our work in interpreting Ground-Penetrating Radar data in MTU/ATU we were invited to join a successful 20+ partner €10m EU project, NetTUN in which we built a D.S.S. to support operators of tunnel boring machines(TBMs) by fusing data from multiple sensors looking ahead of the TBM, cooperating with Universities and companies across Europe, also collaborating with SNCF in a D.S.S. for Tunnel Maintenance(ESWC-15 best "in-use" paper).

Our collaborations with the health sector have had a profoundly beneficial effect on our research activities, driving research in the BMH-Theme in particular, and generating an ICS and further ongoing collaboration and innovation in patient care via the QualDash project deployed into five hospitals(NIHR, Ruddle).

	UK	Europe	Americas	Asia	Other
Universities	42	70	37	34	19
Industry	73	35	12	2	5

Figure-3. SoC collaborations

One of our ICS comes from our early MTU work and the other two ICS demonstrate interactions across two other sectors: rail scheduling and medical imaging. In each ICS we have worked in close collaboration with sector partners, taking inspiration from their needs to develop world leading solutions to important problems. We have worked extensively with cloud computing providers to build energy efficient solutions which have been deployed in industry and led to the *Edgetic* spinout. Collaboration with VET-AI is ongoing and developing computer vision solutions for pet care via a KTP.

Wider contributions to the economy/society

The AI Theme has developed a range of software tools and online resources for the analysis and annotation of Arabic text, with particular application to the Quran and religious studies: https://qurananalysis.com used daily by thousands from across the world.

SoC members have contributed to a variety of bodies across several sectors. E.g. Cohn sits on the Geospatial Commission's (part of the Cabinet Office) National Underground Assets Register Advisory Group(REF3:UOA11-2). Djemame is co-founder of the Heterogeneous Hardware & Software Alliance(HH&S) bringing 20 academic/10 industrial organisations together to advance and exploit heterogeneous hardware(http://heterogeneityalliance.eu/contact).

Contribution to sustainability of the discipline, support for/exemplars of interdisciplinary research; responsiveness to national/international priorities/initiatives

SoC's wide ranging interdisciplinary research has already been discussed extensively(§1). We contribute strongly to all of EPSRC's Prosperity Outcomes (Healthy(AI/BMH), Connected(AC/AI/DSS), Productive(AI/CSE/DSS/BMH), Resilient(AC/AI/DSS) Nations), as well as to the UKRI Digital Economy Theme(DSS). Our research strongly aligns with inter/national priorities in AI, including our contributions to the ATI, and in the EU, most recently with the €20M AI4EU platform project. SoC staff have been involved in the organisation of many conferences, workshops etc, as indicated immediately below. We have made released many software codebases on open source platforms, e.g. ASCETiC mentioned above with >500 downloads, http://openworm.org/downloads.html, and QSRlib(https://qsrlib.readthedocs.io) used in robotics and vision projects. 26 datasets have been deposited in the Institutional Repository since its inception in 2015(https://archive.researchdata.leeds.ac.uk/).

Indicators of wider influence, contributions to and recognition by the research base

Editorships(34) *Editor-in-Chiefships(5):* Artificial Intelligence(Cohn), Spatial Cognition and Computation(Cohn), MICCAI-Elsevier Book Series(Frangi), Progress in Bioengineering(Frangi), Presence(Ruddle). *Associate-Editorships(12):* Computer-Graphics Forum(Carr); International Journal of AI in Education(Dimitrova); Frontiers of AI(Dimitrova), IEEE RAS-Letters(Dogar); Formal Aspects of Computing Journal(Duke), IEEE TMI(Frangi);Medical Image Analysis(Frangi);SIAM Journal of Imaging Sciences(Frangi); SIAM Journal of Scientific Computing(Jimack); IEEE TPAMI(Hogg), Open Research Software(Leng), Peer-to-Peer Networking and Applications(Xu). *Editorial-Board-Memberships(14). Guest-Editorships(3).*

Fellowships etc(10 new, 9 pre-existing): FREng(Cohn), FIAPR(Hogg), FBMVA(Hogg), IEEE(Frangi), EAMBES(Frangi), SPIE(Frangi), Eurographics(Carr), UKCRC(Djemame, Frangi, Hogg,Xu). *Prior to 2014: FEurAI(Hogg,Cohn), FAAAI(Cohn), FAISB(Cohn), FIET(Cohn), UKCRC(Cohn), FBCS(Ruddle, Cohn), Eurographics(Duke).*

Funded Fellowships/Chairs(10): RAEng Chair in Emerging Technologies(Frangi, £2.68M), Marie-Skłodowska-Curie Incoming Fellowship(Dogar; PDRA:Figueredo), EPSRC Leadership Fellowship(Cohen), Leverhulme Early Career Fellowship(Ranner), RAEng Enterprise Fellowship (PDRA:McKee), EPSRC Research Software Engineer Fellowship(Leng), ATI-Fellows(Cohn,Hogg,Ruddle), ESPRC Prize-Fellowships(Ranner, Chew).

Visiting positions (19): Professorships: Cohn: University of Technology Sydney, Tongji University(also High-End Foreign Expert), Qingdao University of Science and Technology, Shandong University; Frangi: KU Leuven; Xu: Beihang University, SWJTU, NUDT, Chongqing University; Atwell: SUSTECH Sudan; Adler: Paris Dauphine University. Visiting Scientists Chinese Academy of Sciences(Frangi); Carr: STFC-Daresbury, Lawrence Berkeley(USA), Los

Alamos(USA), STFC-Appleton; PDRA Bollada: Beihang University; Shakhlevich: Nantes University; Leng: Harwell.

Prizes: ACM-THCI best paper(Ruddle). ACM Computing Surveys Best of Computing Award (Carr), IEEE VIS-19 Test-of-time award(Carr). Donald E Walker Distinguished Service Award, IJCAI-15(Cohn, "honors senior scientists in AI for contributions and service"). Honourable Mention(Runner-up) EurAI Best AI Dissertation Award 2017(PGR:Alomari).10 best papers, 5 runner-up best papers, 1 best video, 1 best poster, 1 best technical implementation, 1 "top cited impact factor", 5 Competition/Challenge awards.

Innovation awards: RCUK Knowledge Base Impact Award 2014; Yorkshire & Humber NHS Innovation Award for Medical Devices and Diagnostics 2014.

International Visitors(staying≥1 week): 33.

Keynotes/invited talks: >100.

Conference organisation:

- Conference/Workshop/Programme Chair positions: >60 + many programme committee memberships.
- Co-organiser with Cai(Madison-Wisconsin) of a 5 month research programme at the Simons Institute for the Theory of Computing (Berkeley) "Counting Complexity and Phase Transitions"(Dyer). Follow up meeting(2017)
- Co-founder of the UK Robot Manipulation Workshop in 2016, hosted in Leeds(2019,Dogar).
- Co-Founder of 3xIEEE Conferences: Cloud Engineering; Decentralised Infrastructures and Applications; Joint Cloud Computing (Xu).
- Dagstuhls co-organised: 14081,16381,14421.
- Spatial Cognition Conference Steering Committee Chair(Cohn)
- UKPEW'2015&2019, GECON'2019 hosted at Leeds(Djemame)

Service to the community(~60):

- EPSRC IT SAT Chair(Hogg)
- EPSRCs e-Infrastructure SAT(Leng)
- UKCRC Executive Committee(Cohn, Xu)
- REF Sub-panellist(Cohn:2014, Hogg, Frangi:2021)
- President-elect International AI in Education Society, previously Finance Chair(Dimitrova);
- Eurographics Executive Committee(Duke)
- Eurographics: International Corporate Secretary(Carr); UK Chapter Chair(Carr)
- ATI University Partners Board(Hogg)
- KR Inc. Director(Cohn)
- Executive Board of IEEE Technical Committee on Business Informatics Systems(Xu)
- IJCAI Executive Committee(Cohn)
- EEE-SRDS SC Member(Xu)
- IEEE-ISORC SC Member(Xu)
- IEEE-HASE SC Member(Xu)
- IEEE-SOSE SC Member (Xu)
- IEEE BigDataService SC Member(Xu)
- EPSRC Peer Review College members (12+1 Associate); AHRC Peer Review College(1)
- Members of UKRI prioritisation panels(9 staff, some multiple)
- Reviewer of EU projects/panels(5 staff)
- Co-chair of IEEE-RAS Technical Committee on Mobile Manipulation(Dogar)
- Chair of BCS Awards Committee and on BCS Academy Board(Cohn)
- Advisory Boards: University of Technology Sydney AI AB(Cohn); NUAR AB(Cohn)
- Various RAEng Committees(Education; Policy; Emerging Technology Chairs: Cohn).
- Scientific Advisory Panel OpenWorm(Cohen)
- Trustee of the Society of Research Software Engineering(Leng)

- Canada Research Council prize panel for two years running(https://www.nserc-crsng.gc.ca/Prizes-Prix/Index_eng.asp, Hogg).

Public engagement:

Extensive outreach activity ranges from training for using facilities (e.g. White Rose & regional N8 grids, the Leeds Powerwalls) to youth education (e.g. the Leeds Headstart summer school), Ada Lovelace outreach events, Leeds' *Be Curious* Festival of Science, Pint of Science, Leeds City Museum Festival of Science, AITech North, Leeds Law Society conference, a robotics event at the Natural History Museum. Cohn appeared in an Audible book ("Days that Changed the World").