Institution: University of York

Unit of assessment: 11 - Computer Science and Informatics

1. Unit context and structure, research and impact strategy
Context and Structure

This submission comprises staff from the Department of Computer Science at York (hereafter referred to as CS). CS research is a central part of the University's vision and strategy. Departmental research is organised under four themes which are detailed below, reflecting the research strengths of CS. As well as making major contributions to core research, CS also contributes to a whole spectrum of research across the University through six interdisciplinary research centres where CS researchers collaborate on a day-to-day basis with other departments. We submitted all category A eligible staff and indicators in this report are based on this group where relevant.

The strength and breadth of this research and its importance to the University's vision helped inform the York Research Strategy (2015-2020) which created seven key research themes across the University (Institutional Level Environment Statement (IES), paragraph 4, 11). Our research makes significant contributions to the themes of (1) Creativity, (2) Health and Wellbeing, (3) Risk, Evidence and Decision Making, and (4) Technologies for the Future. Professor McDermid led the Risk, Evidence and Decision Making theme from 2015 to 2017.

Theme	Research Focus
Critical Systems	Research in this area explores the specification, design and verification of high-integrity and safety-critical systems. Topics include: • Real-Time Behaviour (can a system be proven to always meet its timing requirements?) • Cyber Security (can an autonomous system protect itself from malicious attacks?) • Model-Driven Engineering (can the integrity of a system be improved by exploiting high-level system models?) • High Integrity Systems Engineering (how can critical systems be cost-effectively verified and assured?)
People, Health and Wellbeing	This research theme aims to deliver robust, inclusive, and human-centred computing technology for a diverse range of end users. Topics include: • Safety and reliability in medical applications • Gaming and wellbeing • Accessibility of digital technologies
Analytics	Research in this area explores the study of data, methods for analysing data in different domains, and artificial intelligence techniques for improving our methods of working with large and heterogeneous data. This encompasses novel research on artificial intelligence, computer games, e-Sports, natural language processing and machine learning. Topics include: • Safe decision making in autonomous agents • Big data architectures • Bayesian methods and graphical models

	• Natural language processing • Optimisation and constraint satisfaction
Beyond Human Vision	Research within this theme looks at building a generation of computer vision systems with capabilities that exceed those of human vision, including new algorithms and hardware. This involves studying the techniques and tools for computer vision, image processing and analysis, and pattern recognition. Topics include: • Model-informed visual learning • Novel vision systems • 3D modelling • Computer graphics and image generation

The move away from a research group-based organisation to these broader research themes is part of an overall Departmental and University-wide strategy to promote multi/trans-disciplinary research, which we believe is necessary to enable large societal challenges to be addressed. Each theme has a Theme Champion who is responsible for fostering the research ethos of the theme and encouraging collaboration between themes and beyond CS. The themes are purposefully interdisciplinary and chosen to represent research strengths within the Department, and to integrate with the University research themes and strategy. These themes are broader than our previous research groups to facilitate easier and wider collaboration across multiple areas of research within the Department - most researchers belong to more than one theme. Above the themes, research activity is managed at a Departmental level by the Departmental Research Committee (DRC) and the Deputy Head of Department (Research). The DRC meets quarterly and consists of HoD, DHoD(R), REF Lead and representatives of the research staff, ECRs and PGRs.

Interdisciplinary Centres

CS additionally supports interdisciplinary research across subject boundaries through six research centres which are home to research and researchers from multiple departments:

The **York Cross-Disciplinary Centre for Systems Analysis (YCCSA)** brings together researchers from different departments to develop novel mathematical, computational and analytical methods, and tools for the analysis and modelling of complex systems. YCCSA members are from the Departments of Computer Science, Mathematics, Physics, Biology, Chemistry, Electronic Engineering, Management, History of Art and Environment. This diverse team of researchers works across all seven University research themes.

Digital Creativity Labs (DCLabs) is a centre of excellence for impact driven research in games, interactive media and the rich space where they converge (IES paragraph 11). It is led by York and involves Goldsmiths, the University of Falmouth, and around 100 industrial partners. It is supported by a substantial investment of £18m by EPSRC. DCLabs is strongly involved in the Creativity theme.

The **Quantum Communications Hub (QCHub)** is a collaboration between Physics and CS and is funded as part of the UK National Quantum Technologies Programme with substantial funding of £24m over five years (IES paragraph 11). It focusses on delivering quantum secure communications by drawing on research from Physics and Computer Science. QCHub works within the Technologies for the Future theme.

The **Assuring Autonomy International Programme (AAIP)** is a £12m initiative funded by Lloyd's Register Foundation and the University of York to lead research, training and standards in the safety of robotics and autonomous systems (RAS) (IES paragraph 11). This work is led by

CS academics and researchers and is focussed on both foundational research and technology transfer to industry and regulators. The AAIP works extensively with industry and regulators, through what are referred to as 'demonstrator projects' supporting the assurance of emerging systems and technologies in a range of industries including autonomous driving, healthcare and manufacturing. AAIP contributes significantly to the Risk, Evidence and Decision Making theme.

The **York Interdisciplinary Centre for Cyber Security** brings together expertise across the University of York and internationally to address current and potential cyber security challenges. Areas include IoT, blockchain, cryptographic protocols, quantum and post-quantum cryptography, homomorphic machine learning, cyber security in politics and law, mathematics behind cyber security, and data analysis for encrypted medical data. The centre draws staff from CS, Physics, Mathematics, Law and Management. This centre contributes to both the Risk, Evidence and Decision Making and the Technologies for the Future themes.

YorRobots is an institution-wide initiative, led by CS, bringing together researchers and practitioners with an interest in robotics and autonomous systems, and their applications. The collaboration spans nine departments in the University. The aim of the centre is to maximise the impact of robotics expertise at York to the benefit of UK industry. YorRobots is involved in research into the development of advanced, ethical, safe, trusted, reliable, and certifiable mobile and autonomous robots.

We are the only department to be involved in four of the University's major centres and hubs (IES paragraph 11).

Research Strategy

Our primary research strategy is to be a world leader in research, based on the foundations of international excellence, innovation, impact, collaboration and integrity. Our strategic aims reflect the University strategy (IES paragraph 9):

- Recruit and retain the best researchers at all career stages and offer them an attractive and supportive research environment.
- Encourage and support interdisciplinary research strengths, both interdepartmentally and internationally.
- Deploy Departmental resources to support and build research excellence.
- Recruit the very best postgraduate research students and support the excellent research work of our PGR students and supervisors.

Our previous strategic aims, articulated in REF 2014, were to create world-leading research contributions in *Games and Gaming*; *Inter-disciplinary Research* and *Advanced Architectures and their Applications*. This has been achieved through substantial new initiatives in the Department and the reorganisation around themes.

We are a world leader in *Games and Gaming* through the DC Labs and the Intelligent Games & Games Intelligence Doctoral Training Centre (IGGI), with a team of around 80 staff and students delivering wide-ranging and impactful research in the area. These centres collaborate with hundreds of companies, providing an immensely valuable route to real-world impact. We have won substantial funding to support this area, including £18m from UKRI to support DCLabs, with £10m from EPSRC and companies for IGGI from 2014-2020. IGGI was funded for a second round in 2019, with a total funding commitment of £20m.

We have grown and supported a rich culture of *inter-disciplinary research* to fulfil our goals in that area, through the six research centres listed above. We provide coordination and leadership for four of these centres (YorRobots, YCCSA, Cybersecurity and AAIP) and again have been awarded substantial funds to support these areas, including £12m from Lloyd's Register Foundation and the University of York. QCHub is part of a wider research programme in quantum technologies, which includes the York Centre for Quantum Technologies (YCQT). YCQT is a partnership between the departments of Physics, Mathematics, Electronic Engineering and Computer Science comprising 19 academics from those departments.

Finally, our goals in the area of *Advanced Architectures and their Applications* are being delivered through the Assuring Autonomy International Program, a RAEng Chair in Emerging Technologies, eight funded projects and 40 research staff and students. The Critical Systems theme demonstrates our research strength in this area, and we detail below the substantial number of appointments made in this area. One of the key focusses of the AAIP is in delivering significant industrial impact through demonstrator projects and other collaborations and through work on standards and industrial guidelines.

We have undergone a restructuring of the Department's research, moving from research groups to the theme structure described above, to encourage cross-area and silo-free working, and the six research centres to support inter-disciplinary research and impact. This strategy was formulated with significant input from all research staff, including two research 'away days' held outside the Department where staff had an opportunity to discuss and debate research structures. We have supported these themes through a proactive and very substantial early career academic hiring process and providing substantial support for these ECRs – at the REF census date, we have hired 18 permanent new academic staff since March 2017, including 11 ECRs. The appointments are described in more detail in section 2, but we have made targeted appointments to the themes including eight to Critical Systems, and two each to Analytics, Beyond Human Vision and Health and Wellbeing.

We have world-leading expertise in Critical Systems, including our work on safety, security, enterprise, robotics, autonomous, embedded, and real-time systems. Our vision is to capitalise on this over the next 5 years, by consolidating our new research themes, developing our interdisciplinary centres, and developing new areas of research where appropriate. This includes a plan to grow the academic research and teaching staff to 55 FTE over the next two years from 44 FTE currently. Clearly these plans are dependent on the research environment going forward, which is currently uncertain. Our specific goals over the next 5 years are:

To build on our world-leading status in research in Critical Systems, Safety of Autonomy, Human Vision, Digital Creativity and Games, and Quantum Computing.
- To develop our international reputation in Analytics and People, Health and Well-being.
- To incubate new strengths, particularly in the areas of Software Engineering for Robotics, and Cybersecurity, and support new interdisciplinary efforts in Robotics and Cybersecurity across the institution.
- To establish a synergistic programme across robotics, communications, assurance and verification through the new Institute for Safe Autonomy.
- To carry out cross-disciplinary research both across our research strengths, and throughout the sector as a whole, to maximise impact and particularly impact for the public good.
- To provide the best guidance and research environment for PhD students, including the establishment of a cohort based Graduate School within the Department.

Impact Strategy

Impact is fundamental to the University and Department strategy at all levels. The Department has an Impact Champion who co-ordinates and oversees impact activity across CS. This enables us to develop a coherent impact strategy across the Department. We also work closely with, and benefit from, the University impact manager and the science faculty impact manager (IES paragraph 12). We also have an Industrial Advisory Board (IAB) which includes nine industry practitioners. The IAB is an invaluable channel between Industry and the Department and gives advice on impact, research areas and current industry trends and initiatives. Current IAB membership includes representatives from major companies such as IBM, BAe, and Morgan Stanley.

Our strategy is to generate impact through industry engagement with our research centres. The centres have considerable industry involvement and are in some cases sponsored by industry partners (DCLabs and AAIP), and so they are an ideal route to impact. Our aim is to disseminate the research generated within the themes and centres to these partners and the wider public

and then exploit the opportunities this creates to apply the research in practical scenarios. As an example, we have a large body of research and expertise in the safe design of critical software systems and, as part of this work, we have been involved in setting key international standards in high-integrity systems. For many years we have held continuing professional development (CPD) courses to disseminate this knowledge to software engineers and embed these standards and methods in industrial design. As a result, this work has had major impact on the practice of safety critical systems engineering (see ICS) and was instrumental in the founding of AAIP, which we expect to continue to produce major impact in the future. DCLabs was founded as part of a key initiative to bring together creative industries and new technologies. The WEAVR project, for example, is a £5.8m project running under the umbrella of DCLabs. It aims to develop data-driven content production for e-sports and is the underpinning work which generated an impact case study (see ICS). This is a direct result of this collaboration between computer scientists and the games industry.

As part of our strategy, we have shifted our focus towards projects more directly aimed at impact and knowledge transfer, particularly through Innovate UK and KTP funded projects. These projects give a direct route to impact for our research and are already producing results. KTPs with Rolls Royce, IBM and BAe are tied to our assurance and high-integrity systems work and related to an impact case study (see ICS). A KTP with Gaist developed new strategies for scheduling road pothole maintenance which has been deployed by several councils and was developed into a full impact case study, although it was not selected for the REF. A further Gaist KTP developed a method for the seamless presentation of very large road survey data which has been deployed into a commercial product. A KTP with Balfour Beatty aimed to improve the identification of railway line faults using computer vision and the methods are also now in commercial products.

More generally, the research themes at both the Department and University levels have public benefit at their heart and are designed to ensure our research has national and international visibility. The public interest and potential impact of these themes is evident, and one of the impact case studies is a result of work at the interface between critical systems research and industry (see ICS). We have worked hard to ensure that our themes do not consist of isolated pockets of research, but instead have clear public interest and routes to engagement and impact. One of our impact case studies is the result of making our research open source for the whole community to use, as part of the Eclipse software development project (see ICS).

Open Research

The Department also encourages open access for research outputs in order to generate maximum impact, including papers, code and datasets. The Institutional Environment Statement details the policy for deposit and public availability of research outputs which goes beyond the REF requirements (IES paragraphs 15-17). There has been a cultural shift towards a more open publishing culture within CS, with some outputs being made available on a pre-print archive such as arXiv before submission. The vast majority of CS outputs are published in green open-access venues and are freely available after the embargo period from the White Rose repository. We also encourage the open release of software, and this has led to contributions to the Eclipse Foundation (Epsilon, Emfatic, Hawk, and the foundation of one of the impact case studies), GOBNILP Bayesian network learning software, RoboTool for modelling robotic systems, DOMtegrity (protecting website integrity) and secure anonymous voting software. We have released a number of datasets for general use by the public including machine learning datasets (PRoNTo point cloud shape retrieval, RNA graph dataset) and a family of human head shape models (Headspace, The Liverpool-York Head Model and the York Ear Model).

Research Integrity

The University and Department fully appreciate the importance of research integrity and ethical standards. The University maintains a number of policies on research integrity and ethics (Codes of Practice on Research Integrity, Good Ethical Governance and a policy for the Investigation of an Allegation of Research Misconduct, IES paragraph 14). These policies are implemented at the Departmental level by two designated ethics coordinators who oversee this

process and deal with any ethical or research integrity queries. A faculty-level Physical Sciences Ethics Committee is responsible for the ethical approval of research where required. The Department also has some supplementary policies covering issues more relevant to CS, including a CS ethics approval guide for all research project submissions. All research grant applications must make an ethical statement and put in place appropriate data handling arrangements under a data management plan. The research PI has primary responsibility for the integrity and ethical standards of a research project, but ethical approval must be sought where necessary from the subject-level ethics committee.

2. People
Staffing Strategy

Over this REF period, we have had the opportunity to refresh our academic staff and to strengthen key areas in our new research theme structure. We have focussed particularly on promising young researchers and during the REF period we have appointed 18 junior researchers. We have also targeted senior appointments in national priority areas (Cybersecurity and Digital Economy) with two new Professors since October 2017. Our goal is to strengthen the demographics of the Department for the long term. We have appointed 8 new academics to the Critical Systems theme (Chang, Wright, Matragkas, Gray, Gerasimou, Camera, Liu, Yadav), and others to Beyond Human Vision (Huber, Guarnera), Analytics (Nightingale, Drachen) and Health and Wellbeing (Iacovides, Zendle). We have also appointed a new group of researchers in Cybersecurity (Kahrobaei, Fashim, Shahandashti, Vasilakis). As we noted in the previous REF submission, the appointments are partly driven by a staff profile means that a number of senior researchers have left the Department. We have therefore targeted senior posts where necessary to support the research themes in the Department and to this end have appointed new Chairs of Cybersecurity (Kahrobaei) and Digital Games (Drachen), and internally promoted staff to Chairs in Quantum Computing (Pirandola), Software Engineering (Kolovos) and HCI (Cairns). All except two category A staff submitted are on permanent contracts. These academics are both research fellows appointed to specific funded posts. The mixture of appointments over the REF period puts us in a position where we have a healthy and sustainable mix of staff at all career stages going forward.

The Department aims to support a rich and diverse research culture, and staff mobility forms a key part of this strategy. We have a number of incoming and outgoing international visiting fellows. We have hosted research visits from Italy, Spain, Germany, Portugal, Canada and Brazil. Our staff have held visiting positions at Beihang University, Inria Paris, Universidade Federal de Pernambuco Brazil and Western University Canada. These visiting staff are funded by a range of sources, including research grants, University pump-priming funds and host organisations. We encourage staff to apply for fellowships as a critical part of their development as exceptional researchers at all career stages. This is not limited to research fellowships; we also encourage staff to apply for knowledge-exchange positions. During the REF period, Cavalcanti, Hancock and Cowling have held Wolfson Research Merit Awards, and Habli and Power have held RAEng Industrial Fellowships. Smith was awarded a RAEng/Leverhulme Trust Senior Research Fellowship. Cavalcanti also holds a 10-year RAEng Chair in Emerging Technologies. We have also hosted a UKRI Innovation Fellowship (Foster) and a Royal Commission for the Exhibition of 1851 Fellowship (Giscard).

Staff Support and Development

The University maintains a statement on Research Performance Expectations which outlines our commitment to staff support and working environment as well as the expectations we have of research staff (IES paragraph 22). The Department maintains its own statement on expectations which complements the University-level one with more CS-specific details.

The Department understands the need to support staff development at all career stages. All academic staff undergo an annual personal development review with a senior member of the Department where they can discuss career progress, any problems arising and identify training needs. Other researchers are reviewed by their project leads or line managers. The University

offers a comprehensive skills training programme to support staff development which is detailed in the institutional environment statement (IES paragraph 32). Staff are invited to apply to an annual promotion round. The Deputy Heads (Teaching and Research) offer early-stage support and advice to help staff construct their promotion applications and present the best case to the University.

The Department has launched a new intensive programme of mentoring which is available to all staff. Staff can request one or two mentors to help them achieve objectives related to research (writing a grant proposal, developing a research paper for a leading journal for example) and to teaching. A personal program of mentoring is designed for each member of staff to help them most effectively achieve their goals (e.g., through frequent intensive meetings over a short period of time, through to less frequent meetings over longer periods). Since CS has appointed a significant number of ECRs in the period, we have instituted a new ECR network within CS to offer particular support to ECRs. This involves monthly lunch meetings with invited guest speakers to discuss key topics relevant to this group of researchers, and more informal meetings. Seminars have included discussions of funding opportunities, REF and University research data systems. We have also recently been involved in extending this initiative to a University-wide ECR community.

Study leave forms a major investment by the Department in staff and research development. All academic staff are eligible to apply for study leave which can vary from a single term to a year (e.g. for staff exiting major administrative posts). 15 staff took study leave in the REF period. Examples include Cavalcanti, whose study leave at Universidade Federal de Pernambuco (Brazil) lead to successful grant applications and a Royal Academy of Engineering Chair in Emerging Technologies from research into verification of robotic simulations. Smith visited the UCSD Center for Visual Computing in 2016, leading to two spotlight presentations at leading vision conferences ECCV and ICCV. Pirandola visited MIT to carry out work on quantum communications. Kolovos visited Rolls-Royce, leading to a Knowledge Transfer Partnership, and OTE (Deutsche Telecom Group), leading to further collaboration in an EC Horizon 2020 project on polyglot persistence architectures for big-data analytics.

We support all staff in the development of research impact through an impact champion in the CS department and a faculty-level impact manager. The impact champion is responsible for disseminating impact opportunities to researchers, supporting CS researchers in the development of impact and promoting awareness of the value of impact. The faculty impact manager is available to give advice on impact in research projects at all stages from proposal development to the post-project phases. We expect researchers to consider impact throughout the development of a project, from conception to publicising the final outcomes.

To maintain strong links with industry, we have a number of visiting professors in the Department. Whittington (MooD International) and Morgan (ETAS Ltd) are RAEng-sponsored Visiting Professors. Many of our industry links are directly through research projects and centres. Our funding strategy has in part been to encourage more direct links through InnovateUK and industry funded projects. The AAIP programme is directly funded by Lloyds Register Foundation and we have substantial research portfolios with BAe Systems (£233k), Rolls Royce (£155k) and IBM (£157k). IBM also had a team physically located in the Department for part of the REF period to enhance interactions with academics. Staff have been actively encouraged to engage in knowledge transfer activities and have succeeded in undertaking 25 projects funded by InnovateUK (£1.9m), including 8 Knowledge Transfer Projects.

The University is fully engaged with The Concordat to Support the Career Development of Researchers and has held the European Commission's *HR Excellence in Research Award* since 2010. There is an action plan for 2018-2020 to support implementation (IES paragraphs 27 and 28) with some actions to be implemented at the Departmental level. There is a robust set of procedures and policies to be followed at the Departmental level for the recruitment and selection of researchers (Principle 1). All research staff are treated as full members of staff, and so have the same access to mentoring, skills training and performance review (Principles 3 & 4).

This demonstrates that we recognise the importance of researchers to our research environment (Principle 2). Researchers are made aware of their responsibilities and opportunities by their line manager (usually the PI) when they are appointed (Principle 5). Diversity and Equality issues (Principle 6) are addressed through our initiatives which apply to all staff and are described in the next section. The University undertakes regular review of progress in this regard at all levels (Principle 7). The Department is committed to trying to retain staff on fixed-term contracts where possible and has provided resources to bridge researchers between research contracts where appropriate.

Support for Equality and Diversity

The University has a comprehensive set of policies to support equality and diversity (IES paragraphs 35-37), which are all implemented by the Department. We have appointed an Equality Champion and initiated an Equality Committee which meets monthly. A set of webpages has been created detailing our support for equality and diversity, and our "zero tolerance" policy for any discrimination by staff or students has been widely publicised. The Department supports flexible working for staff; full-time staff may choose flexible working hours outside our two core time periods. We have policies for parental leave and staff may ask for flexitime arrangements to support their personal circumstances. We also consider requests for special arrangements when constructing the Department timetable annually. The University has an on-site nursery to help support staff with young children. We reviewed our recruitment materials and websites to ensure they give a positive and welcoming impression to all groups.

Over the past four years, the Department has undergone a thorough review of our activities surrounding equality and diversity under the guidance of an Athena Swan and Equality Champion (Petrie). We developed a new Athena Swan submission and, as part of that process, we considered broader diversity issues beyond gender. The result of this work was the formation of the Athena Swan Self-Assessment Team (SAT) and a comprehensive action plan for improving equality and diversity. Many of the points on the Action Plan will not only support women in the department, but also will greatly improve the study and work environment for everyone. We believe this will also make it easier to expand our support to other under-represented groups, including staff and students with disabilities and from different backgrounds. The action plan consists of 10 high-level objectives and 60 detailed actions which will be monitored and implemented by the Department over the next few years. These include a new 'best practice' (from Informatics Europe) recruitment process to encourage female applicants for all teaching and research positions. The SAT is engaged in all aspects of the recruitment process, from review and revision of advertisements focusing on E&D issues, to monitoring shortlisting and interviewing, to post-mortems on recruitment efforts (e.g., hiring panels) for effectiveness assessment and future enhancement. We plan to improve the working environment and to this end we have set up a network of women academics and researchers who meet once a month for lunch to discuss issues in a more informal setting. We also aim to improve the support for staff development through briefing and mentoring on topics including promotion, preparation for REF and training. Many more such initiatives are included in the action plan.

The selection of outputs for submission to REF2021 was made within the framework of the University's REF Code of Practice, which has robust procedures for ensuring transparency, consistency, accountability, and inclusivity. A REF strategy group monitors the selection process for any signs of bias. All Category A eligible staff are included in our submission and decisions about research independence were made at University level, informed by an equality impact assessment (EIA). The EIA was considered carefully at Departmental and University level. Output selection was based on the primary criterion of quality, informed by at least two expert reviewers and with recommendations from a CS REF committee. Within the constraints of this criterion, we aimed to distribute outputs as widely as possible among staff. All staff were given feedback on their selected papers and opportunity to comment. The composition of the CS committee, recommendations and rationale behind the selection were reported to the University to ensure transparency and accountability of decisions. Our analysis of the selected papers

does not show any statistically significant difference in papers submitted per researcher or in estimated paper quality, on the basis of either gender or ethnicity.

Research Students

Research students are a critical component of our research community and we have a large and growing PGR cohort who produce outstanding research. We expect our research students to carry out original and rigorous research and communicate results to the widest possible audience. As evidence of the high quality of our students Dale (Stepney and Trefzer) won the 2019 CPHC/BCS Distinguished Dissertation competition and Aziz (Wilson and Hancock) was a runner-up in 2015. We aim to attract high quality students to apply to our PGR programmes and to ensure that the Department effectively monitors and supports them while there are here. It is important that PGRs feel they are part of the research team in the Department, and so they have the status of full staff members. We have created an online space for PGRs including a PGR Community Page and PGR newsletters.

We recruit students from an extremely varied set of backgrounds. We have PGR programmes leading to MSc by research, MPhil and PhD, with most of our students studying for PhD degrees. We offer full-time and part-time degrees and a distance-learning option. These courses help us cater for students with a diverse set of circumstances and needs. The part-time distance-learning degree has been particularly successful in widening access, allowing students from non-traditional backgrounds to study for a PhD, for example mid-career professionals who have to maintain a job while studying and those not able to travel regularly to the University. As mentioned in the previous section, we have worked hard to ensure our recruitment material and interview processes encourage and support applicants from all kinds of backgrounds. We are developing a 'buddy' system for applicants to allow them to ask questions of our current PGR students with a similar background, where possible. Students are funded through a variety of mechanisms, including self-funding and external sponsorship, the IGGI CDT, University scholarships and Departmental scholarships. The scholarships are awarded through a competitive process which considers both merit and the needs of the student.

The PGR programme is managed by a separate Research Studies Committee under the framework set out by the University (IES paragraphs 30-34). The RSC implements a detailed timetable of checkpoints and assessments aimed at making sure every student achieves their goals and gets the help they need. Each research student is allocated a Thesis Advisory Panel (TAP) consisting of a supervisor, assessor and panel chair. The supervisor offers ongoing support and typically meets the student every week, and at least every two weeks. The student must complete a milestone every six months, which has the dual purposes of allowing the assessor to check progress and allowing the student to develop research presentation skills. A Progression Panel is held at the end of each year of study (or full-time equivalent for part-time study) where a group of senior academics meets to consider the progress and progression of all research students. The Progression Panel is carefully selected to have a range of backgrounds and to ensure that members are fully aware of equality and diversity issues that may affect candidates. Students are able to seek support from their supervisor, assessor or the Chair of Research Studies as appropriate. The assessor holds a confidential review of supervision at each milestone to identify any problems with supervision arrangements. Our goal is to enable students to submit a thesis as close to the target date as possible and to maximise the number of students that complete. All PGR students have access to desktop machines in the Department, and we have recently created a dedicated PGR space where students can work and meet to discuss their research. This is part of our long-term goal to move towards a cohort-based graduate school where students can interact more frequently with each other.

All research students undergo an induction at the start of their course, including a series of talks and an introductory booklet. The department has an active training program and a PGR student training officer. The program focuses on careers and skills development and has a set of core compulsory modules (Research Integrity, Becoming an Effective Researcher, Professional Development Planning) along with a range of more than 50 skills development courses. Students who plan to teach must also take 'Introduction to Teaching and Learning' delivered at

University level. The skills development courses include careers, legal and ethical issues, research management, impact and communication. The training officer supports the doctoral students in running the York Doctoral Symposium, an event that is organised by students for students, and which is in its eighth year. It attracts around 70 attendees, including external participants. The students also run a student-focused seminar series on topics of specific interest, such as preparing for a PhD viva. For students on our CDT programme, there is additional specific training. Many PGRs also support our teaching programme through demonstrating.

3. Income, infrastructure and facilities
Research Funding

Total research income reported in REF4b was £26m, as compared to £19m in REF2014. Our strategy at the previous REF was to reduce dependence on UK industrial and government funding by targeting EU income. This strategy was successful; we reported £3.92m of European Commission funding for REF 2014, and we have £7.7m in the current REF period. Wider events have triggered a change in focus and towards the end of the current period we have shifted our income generation away from EU sources and towards projects more directly aimed at impact and knowledge transfer. We have substantially increased our Innovate UK income, for example, to £2.9m in the REF period (income includes directly funded and KTP funded projects). This will allow us to generate high-impact outcomes for our research. We have maintained our level of research council funding over the period to support our 'blue-sky' research. Research council funding and PGR students are our main drivers of high-quality research outputs. Our forward-looking strategy is to continue to seek funding from UKRI, while engaging more with the Grand Challenge Research Fund (GCRF) and the Industrial Strategy Challenge Fund, as these are well aligned with our themes and University strategy. We also plan to seek larger, collaborative projects involving more staff at York (in CS and across other departments), and other institutions, and to continue to promote fellowships for our research staff.

We aim to support our research themes and centres with significant research funding. The Digital Creativity Lab has £18m of funding from UKRI, University partners and industrial collaborators (IES paragraph 11). DCLabs is critical to support and enhance our research in Analytics. The Assuring Autonomy International Programme (AAIP) is tied to our work on critical systems and is a £12m commitment by Lloyd's Register Foundation and the University of York. The work in Assuring Autonomy and Robotics is also being provided with a purpose-built facility via an RPIF bid (£10m, discussed in the next section) and an additional £4m provided by the University. The Intelligent Games and Game Intelligence (IGGI) CDT has been funded to a value of £5.6m by EPSRC and in total attracted £10m in funding in the first instance. The Centre won continued funding in 2019 for another eight years, with a grant of £8.2m from EPSRC, York and QMUL matched funding of £2m each, and industrial commitments in kind of £7.6m. The Quantum Communications Hub is a collaboration between CS and Physics at York (IES paragraph 11) which is one of four hubs funded as part of UK National Quantum Technologies Programme, with £120m being committed for the four hubs. As well as this hub, we are coordinating an EU project on quantum readout techniques and technologies (QUARTET) and are part of an EU flagship grant (CiViQ, €10m). We have also been awarded substantial grants at the interface between software engineering and physical systems (INTO-CPS European Commission £700k, RoboCalc EPSRC £1.8m, RoboTest (jointly with Sheffield) EPSRC £1.1m). The area of real-time systems continues to attract significant funding with two substantial EPSRC grants (£593k for multi-core research and £934k in cyber-physical systems).

One of the outputs of our research into critical systems is a set of standards and methodologies for engineering safety critical systems see Autonomy ICS). One of our routes to impact for this work is through a series of professional development courses on safety-critical systems engineering, training engineers from industry to apply state-of-the-art methods. This activity brings around an additional £800k pa to the Department.

Infrastructure and Facilities

We continue to support experimental facilities in CS in the form of laboratories hosted largely within the CS building. These support empirical research in each of our four research themes and are listed below. We have also won a £10m award from the Research Partnership Investment Fund to provide a state-of-the-art building supporting research in Autonomous Systems. This Institute for Safe Autonomy Building will host our research in assured autonomous systems, verifiable robots and safety assurance, and is additionally funded by £4m from the University.

The *HCI Interaction and Home Labs* comprise two usability laboratories, three domestic environment labs (a kitchen, living room and dining room), and a control room with specialist equipment for usability research, games research and research with disabled and older people. Equipment includes a range of input devices, screen-readers, screen magnification programs, discreet webcams, eye trackers and screen capture software to monitor activities.

The *Real Time Systems Lab* supports real-time hardware analysis and sensor networking research. This lab has been updated with a range of FPGA boards (cost £20k) and 4 GPU servers (£80k). The separate Crossrail Lab provides facilities for student teaching and individual projects in embedded and real-time systems and has been provided with 170 FPGA boards (£25k).

The *Computer Vision Lab* suite comprises a dark room and natural light laboratories. Equipment includes a laser range scanner (Cyberware 3030PS) for acquisition of calibrated shape, texture and reflectance data, and optical bench and light stage facilities for polarisation imaging, spectro-radiometery and photometric surface analysis. The lab supports the work of the 'Beyond Human Vision' theme. The labs were refurbished in 2019 using £30k of Department funds. The lab has been used to collect data for 18 research outputs during the REF period.

York Robotics Laboratory (YRL) (shared with the Department of Electronic Engineering) is a purpose-built facility for experiments in robotics, including autonomous systems. The lab is equipped with state-of-the-art tracking systems, a teaching/research classroom area and a technical workshop area. It provides safe, constrained space for empirical testing of theories in robotic and autonomous system behaviours, e.g. swarms of airborne systems and underwater systems. The lab supports work in the Analytics theme and the AAIP centre, and employs a full-time technician, shared between CS and Electronic Engineering.

We aim to make the most of our research space to help generate impact from our work. *DCLabs* is a group of around 30 researchers hosted in a separate facility in the Ron Cooke Hub, adjacent to the Computer Science building. This facility enables researchers from multiple departments to come together with industry partners in one space. The RC Hub contains offices, interactive spaces, break-out zones and seminar rooms, and rents space to small companies and start-ups as well as hosting CS academics. The dedicated institute mentioned above for Assured Autonomy and Robotics will bring together researchers from multiple departments into a building with state-of-the-art facilities. A key part of the building design is a shared collaboration space which aims to enable interaction between academia, government and industry and enhance research impact. The Campus-based Catalyst building and the Science Park are close to the Department and host innovative companies as well as several spin-outs, who collaborate with researchers in the Department.

Research Students are a critical part of our research landscape and we provide them with the best possible facilities for carrying out their research. PGRs are treated as members of staff in terms of access to facilities and resources. Each PGR has access to a desk and desktop computer within the Department. We have recently invested in a bespoke PGR space which aims to house many of our students in the same space, so that they can collaborate, share ideas and experience, and support each other during their studies. This aims to foster a strong sense of community amongst the PGRs. PhD students also automatically receive an £1800 travel grant to support conference and meeting attendance during their PhD.

Much of the work in the Department requires significant computational support. Some of this infrastructure is provided at the University level and is accessible to all departments. The York Advanced Research Computing Cluster (YARCC) is a heterogeneous cluster of 70 nodes and 1462 cores provided by the University, with 8 nodes supported through the IGGI CDT. The Viking cluster is new in 2019 and represents a £2.5m investment in a 173 node 7024 core computing facility. It also contains 8 NVIDIA GPUs specifically for improved machine learning performance. Most recently, the N8 Centre of Excellence in Computationally Intensive Research has begun to deliver the Bede facility (available to all researchers in the N8 Universities) with 32 IBM dual Power 9 CPUs. The Department has also invested in computing facilities, particularly for machine learning. Equipment to the value of more than £100k has been provided for researchers through direct spending and equipment gifts. They support two compute servers with a value of ~£40k and provide four GPU servers with a value of more than £40k.

Operational support

We have a CS-specific Research Support Office (CSRSO) with 3 dedicated staff to support all aspects of research. This including grant preparation and administration. They operate a grant proposal review system which is also supported by the academics in the Department to help maximise the quality of grant submissions. They also ensure the proper ethical consideration is given to research funding. They also help academics organise conference hosting and management of publications. Each of our research centres also employs a dedicated manager to support their work. We have 14 technical staff to support computing infrastructure and all aspects of the infrastructure for our research including hardware and software. The technicians have a dedicated hardware workshop for building computing equipment. We also have an Impact Champion as a distinct role in the Department. The Impact Champion works closely with a faculty-level Impact Manager to support all aspects of research impact from the conception of a project to commercial impact in industry. Our Athena Swan and Equality Champion oversees our efforts towards improving the working environment of the Department for everyone. We also have a Disability Coordinator who ensures that all disabled members of the Department have access to the support they need to access our facilities. The DC also liaises between the Department and University to help support those with disabilities.

The University is part of a number of collaborative groups including the White Rose Partnership (with the Universities of Leeds and Sheffield) and the N8 group of research-intensive northern universities (IES paragraph 6). The White Rose Partnership aids the Department in a number of ways. It provides a repository for all our published papers and supports our drive to open-access (IES paragraph 16). More than 900 research outputs (in the REF period) are available on the repository, the vast majority of which are publicly available due to gold or green open access. The N8 group has helped to deliver advanced computing facilities to CS through the Centre of Excellence in Computationally Intensive Research.

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

CS is an extremely outward looking department and has large numbers of research collaborations from all areas of the world. For example, SciVal reports that CS published papers with 847 different institutions outside the UK in the REF period. The Department encourages research collaboration through a number of mechanisms. It manages a substantial discretionary fund which is distributed to research staff for pump-priming and other research activities including collaboration, impact and research meetings. The average size of the fund was £172k pa over the REF period to the end of 2019. CS also runs a programme of study leave with an open call to all members of staff to enable members of staff to focus on research for a period, and this includes support for research collaboration costs. Study leave has been used to develop collaborations with a wide variety of institutions such as Universidade Federal de Pernambuco (Brazil), Boston University, University of Washington, University of Oxford, UCSD and MIT. We also encourage staff to become involved in research networks and to apply for research fellowships.

Fellowships

Over the REF period, members of staff have held a number of prestigious funded research fellowships at York. Cavalcanti held a Wolfson Research Merit Award from 2012-2017 and currently holds a Royal Academy of Engineering Chair of Emerging Technologies. Hancock and Cowling had Wolfson Research-Merit Awards (2009-2014 and 2017-2022 respectively). Pears held a RAEng/Leverhulme Senior Research Fellowship (2013-2014) as did Smith (2019-2020). We also hosted the Royal Commission for the Exhibition of 1851 Research Fellowship of Giscard at York (2015-2018) and Gaetana Spedalieri holds a Marie Curie Global Fellowship (2017-2020).

Our staff also hold significant visiting positions outside York. Cavalcanti was Visiting Professor at Universidade Federal de Pernambuco, Brazil (2017 funded by Royal Academy of Engineering). Hancock is Distinguished Visiting Professor at Beihang University and Xiamen University. Davis held an Inria International Chair at Inria, Paris (2014-2018). Bate was a Docent Professor at Malardalen University, Sweden (2011-2016, funded by Stiftelsen för Strategisk Forskning (SSF)). Woodcock was Visiting Professor at Universidade Federal de Pernambuco, Brazil (2017 funded by Royal Academy of Engineering). Power is an Adjunct Research Professor at Western University, Canada (2016-2021). Kahrobaei is an affiliated Professor at the City University of New York and a Visiting Professor at the Institute Henri Poincare and the Sorbonne University. Indrusiak was a Visiting Professor at UFRGS, Brazil (2014, funded by Capes). In total, York academics have held 20 visiting positions outside York during the period.

We also have a number of links with industry through fellowships and secondments. Habli and Power had RAEng Industrial Fellowships in 2016, Habli with NHS Digital and Power with IBM. Geoff Garnett (DSTL) is a Visiting Professor.

Networks

Networks play a key role in creating long term collaborations between York and researchers in other institutions. Smith was dissemination coordinator for the EU COST Network on Integrating Vision and Language. The network involved more than 50 researchers from 28 countries. Cavalcanti is part of the EPSRC network on robotics and autonomous systems, involving around 30 Universities. Cussens is network topic leader in the EPSRC network on Human-Like Computing. Calinescu, Woodcock, Cavalcanti and McDermid are members of EPSRC network on the Verification and Validation of Autonomous Systems. Indrusiak in involved in the EPSRC network eFutures and the EU network HiPEAC. Kolovos is part of the MDENet EPSRC network on model-driven engineering. Shahandashti is an Expert Fellow in the SPRITE+ network on security. Foster is a member of the EU network for safer autonomous systems.

We support interdisciplinary research mainly through the work of our centres YCCSA, DCLabs, QCHub, AAIP and Cyber-security. These enable researchers from multiple departments to work on problems of interest at the interface between subjects. This approach has fostered a number of interdisciplinary research projects. RoboCalc and RoboTest (Cavalcanti, Woodcock) are a collaboration with Electronic Engineering. SpInspired (Stepney, O'Keefe) is an EPSRC project involving both Chemistry and Electronic Engineering. TARGeTED (Stepney) includes researchers from Physics and Chemistry. The Weavr consortium is a UKRI funded £4m project to look at e-sports broadcasting, and involves CS and Theatre, Film and TV with a consortium of five companies. Archival Polar Photography (Hancock, Smith) is a collaboration with Environment and Geography. Pears and Smith have a project with Hull-York Medical School on head shape modelling. The Wearable Clinic project is a collaboration with Health Economics and Health Services. 'Mathematical Modelling of Bi-Directional Synaptic Signalling' (Calinescu) is a project with Structural Biology researchers from Oxford. We also have a number of PGR students who are co-supervised across more than one department and, through the IGGI programme, students across more than one institution.

Visitors

The research themes host both national and international visitors as a matter of course. Over the REF period, we have hosted 29 research fellows, including Lisane Brisolara (UFPel Brazil),

Lars Kunze (Oxford) and Chris Storm (Adelphi University, USA). Our research centres are instrumental in attracting research fellows, with a significant number of fellows visiting from industry as well as academia. We have hosted visiting fellows from BMW, Bosch, Hewlett Packard and DSTL.

Engagement with research users

Industrial collaboration is one of the key strengths of the Department. We have close links to more than 100 companies through their sponsorship of the IGGI CDT, and this provides a direct route to impact for much of the work in the Analytics theme (see ICS) . Similarly, the AAIP engages directly with end-users through industry partners and demonstrator projects. AAIP directly funds knowledge transfer to the wider community through a number of mechanisms. They maintain a body of knowledge on best practice in the area of robotics and autonomous systems distilled from many years of research. They also deliver a training and education programme including academic qualifications in safety critical systems engineering with RAS assurance, onsite and online training, workshops, and informal learning opportunities.

Our staff collaborate extensively with companies through a variety of mechanisms including visits, advice and consultancy, funded projects, joint research papers and technology transfer initiatives. We hosted collaborative projects with around 70 other companies, including some of the largest companies in the world (e.g. Microsoft, IBM, Fujitsu, BAE, Airbus, NHS). We also have a significant route to impact through our CPD courses on safety-critical systems engineering (see ICS), which have trained more than 600 engineers from industry in the application of state-of-the-art software engineering method developed in the Department. These engineers come from diverse backgrounds, coming from 12 different countries and more than 100 companies.

Wider influence and contribution to the research base

CS has been involved with a large number of activities to engage with the wider research community. We have hosted many conferences and workshops over the REF period. Of particular note are; the British Machine Vision Conference 2016 (300 attendees, 2 invited keynotes, 11 industry sponsors including Disney, HP, nVidia and ARM), Software Technologies: Applications and Foundations 2014 (210 attendees, 6 invited keynotes) and the European Conference on Artificial Life 2015 (200 attendees, 4 keynotes). Our staff gave more than 100 invited keynote presentations at conferences and workshops and lectured at 8 summer schools/tutorial meetings. We fulfilled 42 Programme/General/Co-chair roles in conferences and workshops. The following have held Editor-in-Chief roles at journals: Hancock (Pattern Recognition), Woodcock (Formal Aspects of Computing), Kahrobaei (International Journal of Computer Mathematics: Computer Systems Theory), Burns (Leibniz Transactions on Embedded Systems) and Bate (Journal of Systems Architecture). Members of staff hold another 24 positions on editorial boards. Academics regularly engage in the external examining of PhDs in the UK and throughout the world, with 90 exams in the period. The strength of our international links is evidenced by the fact that more than half of these (51) were overseas.

Our work has been recognised as outstanding by the community, as evidenced by the recognition awarded to our researchers and research outputs. We gained 28 best or outstanding paper awards in the period. Dale (Stepney and Trefzer) won the 2019 CPHC/BCS Distinguished Dissertation competition and Aziz (Wilson and Hancock) was a runner-up in 2015. Hancock was made a Fellow of the IEEE, a Distinguished Fellow of BMVA, gained the IAPR Pierre Devijver Award in 2018 and an Honorary Doctorate of the University of Alicante in 2015. He is also an Honorary Professor at Anhui and Beihang Universities.

Members of the Department regularly engage with research users and the wider public through policy making bodies, outreach and public engagement events. Cairns contributed evidence to government committees in both the UK and Australia on the problems of game loot boxes. Likewise, Zendle has been extensively involved with forums and policy-making bodies on the issues surrounding loot boxes. Cairns and Power have worked with the AbleGamers Charity supporting gamers with disabilities. Shahandashti was involved with the trial of verifiable e-

voting systems in Gateshead. Members of staff have presented their work on BBC radio and at many public engagement meetings. In total, academics have spoken at 21 public engagement events. We host a Departmental seminars with invited speakers from national and international institutions. We have also invited distinguished external talks as part of our 'Roundhouse' public lecture series. Speakers include Sir Michael Brady (2015) and Sir Tony Hoare (2015). The University has also recognised prominent computer scientists from around the world with honorary degrees, including Sir Michael Brady, Bertrand Mayer, David Braben, Tieniu Tan and Narendra Ahuja.

Leadership and Informing Strategy

Members of staff have also made substantial contributions to the wider research landscape. Hancock was Vice-President of the IAPR (2016-2018) and sat on the Royal Society panels for International Exchanges, Newton Fellowships and Research Appointments. He chairs the IAPR Maria Petrou prize committee, is on the REF 2021 panel and chaired the Czech Academy of Sciences CS Assessment Panel (2016). Woodcock chaired the Microsoft Verified Software Award Committee, the Formal Methods Europe Prizes and Awards Committee. He also sat on the committees for the RAEng Awards, RAEng Newton Fund and the Grand Challenges Research Fund. Stepney was a member of EPSRC's ICT Advisory Team, the Science, Engineering and Technology Board and the "Big Ideas" Advisory Group. She is also vice-president of the International Society for Artificial Life. Cavalcanti was a Royal Society Newton International Panel member. Wilson was a member of the Czech CS Assessment Panel (2016, 2020). Cairns and Zendle have provided evidence to support policy changes surrounding game loot boxes and gambling. Members of the Department are also extensively involved in reviewing and assessing research proposals from research bodies all over the world.