Institution: University of Hertfordshire

Unit of Assessment: 11 Computer Science and Informatics

1. Unit context and structure, research and impact strategy

Computer Science research at the University of Hertfordshire is carried out within the Centre for Computer Science and Informatics Research (CCSIR), which provides purpose-built research laboratories and accommodation for the current 12 research fellows and 58 research students. The CCSIR comprises three main research groups: Adaptive Systems, Algorithms and Biocomputation. It has a substantial degree of funding and financial autonomy as QR research income is, after modest top-slicing by the University, distributed across UOAs, against approved research delivery plans and according to their REF 2014 outcome.

In addition to being affiliated with CCSIR, academic staff in Computer Science are based in the newly founded School of Physics, Engineering and Computer Science (SPECS), with the aim to encourage increased collaborations between these three disciplines. The Unit submission for REF 2021 is 31.2 FTE, which constitutes a 14% increase in size compared to REF 2014 (27.4 FTE).

Notable improvements and successes for the Unit within the period in comparison with REF 2014 are:

- The experiential balance of staff with 33% Professors and Readers, 43% lecturer staff and 24% early career researchers.
- Doubling of the percentage of BAME staff to 44%.
- Research culture ranked as 3rd among 32 HEIs submitting in Computer Science in the 2019 Postgraduate Research Experience Survey with satisfaction levels of 92% for research skills and 88% for supervision.
- Secured an EPSRC infrastructure grant in 2017 for upgrade to the Robot House 2.0 and to operate it as a national specialist facility.
- Unit member elected as President of the international Organisation of Computational Neurosciences from 2019-22 (Steuber).

Strategy

The four strategic aims identified in the REF 2014 submission have been pursued during this cycle.

Strengthen areas of excellence. The main research concentrations remain Adaptive Systems (including health robotics, human-robot interaction, information theory driven artificial intelligence, artificial life) and Biocomputation (including computational neuroscience, machine learning and algebraic biology), with Adaptive Systems providing significant research impact and Biocomputation, in particular, producing research outputs in major journals. The Unit's strategy in the current REF cycle has involved reinforcing these two areas by making targeted staff appointments and by securing external funding to stimulate further growth. Since 2014 two lecturers and two senior lecturers in robotics (Koay, Wood, together with Foerster and Walters, previously employed as research fellows), a principal lecturer in artificial intelligence (Kim, previously senior bioinformatician at Kew Royal Botanic Gardens London), a senior lecturer in neuromorphic computing / data science (Schmuker, from the University of Sussex) and a senior lecturer in machine learning / computational neuroscience (Kadir, from Imperial College) have been appointed. These staff members have already contributed more than 30 articles in journals such as Nature Neuroscience, PNAS, elife, Scientific Reports, Neural Computation, IEEE Transactions on Human-Machine Systems, etc., and they have been involved in successful funding bids such as an EPSRC Robot House grant, the EU Flagship Human Brain Project and MRC/NSF NeuroNex grants, thereby additionally strengthening research in the Unit's priority areas.

Expand interdisciplinary research. A growing collaboration between the Biocomputation Research Group and the Centre for Astrophysics Research at the University has culminated in the creation of the University-approved interdisciplinary Centre of Data Innovation Research (CoDIR) that currently comprises six lead members: Steuber, Schmuker and Kadir from Computer Science and Geach, Jones and Kaviraj from Astrophysics. The creation of CoDIR as a research centre that combines expertise from biocomputation and astrophysics has been inspired by the insight that many difficult problems in both fields can be tackled by the same techniques of data analysis and machine learning. CoDIR intends to not only pioneer innovative data science techniques – in particular, by exploiting expertise in machine learning and computational neuroscience – to advance the field of survey astronomy, but also to develop a strategy to translate these techniques to other disparate areas, with a particular focus on medicine, neuroscience, defence and agritech. Data science, machine learning and biocomputation are some of the main areas for the future expansion of interdisciplinary research, both in terms of finding new application domains in collaboration with partners in industry and in terms of developing and improving new techniques such as topological data analysis for biological data (Kadir).

Several other new interdisciplinary initiatives have been facilitated by securing external funding, such as a NeuroNex grant from the American NSF and the MRC (Schmuker), and through internal investment from the University. For example, the University has created three 5-year Vice Chancellor's Research Fellow (VCRF) positions in Information-theoretic Artificial Intelligence; Biocomputation, Mental Health and Wellbeing; and Neuromorphic Machine Learning; together with three Early Career Research Fellow (ECRF) positions in Healthcare Robotics; Systems Biology for Food and Disease; and Predicting the Impact of Airborne Particles on Crops, to work on collaborative interdisciplinary research projects with other universities (e.g. Department of Life Sciences, Kings College London) or other Schools in the University.

Increase extra-academic impact. As described in the subsection on the Unit's Impact Strategy below, engagement with research users outside academia has been strengthened. The industrial exploitation of the Unit's research through new Knowledge Transfer Partnership (KTP) projects and by bringing the Kaspar robot for children with autism spectrum disorder to the North American and Japanese markets, supported by a recent license agreement with the Canadian company Compusult, has been increased. Further public impact has been stimulated by work with the NHS, and with hospitals and also schools in eight different countries, and through a large number of exhibitions and art works by the Unit's Artists in Residence Anna Dumitriu and Alex May (see below).

Raise international profile through collaboration and leadership. In addition to further developing international collaborations (see Section 4), Unit staff have continued to raise the international profile of the Unit by taking on academic leadership roles. These have included elected positions as President of the RoboCup Federation (Polani) and as President of the international Organisation for Computational Neuroscience (Steuber), a Membership of the ACM Distinguished Speakers Program (Dautenhahn) and Chair of IEEE/CIS Taskforce on Artificial Life and Complex Adaptive Systems (Nehaniv).

Interdisciplinary Research

Much of the research in CCSIR is interdisciplinary and involves collaborations with partners within and outside the University. Following REF 2014, research in the University of Hertfordshire has been centrally restructured around six main Research Themes: (1) Information and Security; (2) Health and Wellbeing; (3) Food; (4) Space; (5) Global Economy and (6) Heritage, Cultures and Communities. These University-wide, global challenge focused Themes were created in order to foster interdisciplinary research across different research centres and UOAs. Each of the themes is led by a Theme Champion who interacts with the other Theme Champions and Associate Deans (Research) to stimulate new collaborative initiatives with partners within and outside the University, such as the joint projects between Computer Science and the School of Life and Medical Sciences with Lister Hospital and Princess Alexandra

Hospital on robotic surgery, data science and gerontology. Computer Science research is particularly associated with the Information and Security Research Theme which organises both internal and external facing networking events to stimulate interdisciplinary research partnerships.

Interdisciplinary collaborations are also facilitated by providing travel funding. Staff are additionally encouraged to apply for external funding for interdisciplinary projects with international partners. External visitors, such as Professor Jim Bower who has played an important role in establishing Computational Neuroscience as a discipline and who is a Visiting Professor and regular visitor in the Biocomputation Research Group, are welcomed on a regular basis to the Unit for extended visits. More detail of interdisciplinary research collaborations with partners outside the University is given in Section 4.

The CCSIR, which hosts all postgraduate research students and postdoctoral research fellows in computer science, is located in direct vicinity to other research centres in physics, mathematics and astronomy, and also engineering, with joint discussion rooms and kitchen facilities. It is not a coincidence that a productive collaboration between computer science and astronomy has developed (around the application of machine learning to the classification of galaxies), with a publication in Monthly Notices of the Royal Astronomical Society and media exposure on BBC Radio 4.

An important interdisciplinary initiative between Computer Science and Astronomy is the Centre of Data Innovation Research (CoDIR) (see **Expand interdisciplinary research** above), which has led a successful development of an internally funded new £300k Data Science and Visualisation Lab to be utilised by a range of staff from computer science and astronomy as well as creative arts, life and medical sciences and engineering. The three new VCRFs and three new ECRFs noted above have been appointed to conduct interdisciplinary research in various collaborative areas.

Impact Strategy

Industry engagement and commercialisation of research. Engagement with research users outside academia is a central part of the Unit's impact strategy. Staff work together with the Information and Security Research Theme Champion and the University Enterprise and Business Development Innovation Team to establish externally funded KTPs with industry; this involves the establishment of contacts between companies and academics and the organisation of workshops for representatives from industry that are interested in specific areas such as machine learning. Recent KTPs with Manor Pharmacy Group, Heales, Intelligent Voice and Advanced Collection Systems involve the application of machine learning to applications ranging from voice recognition to occupational health and pharmacology (led by Helian, Sun and Veneziano), and a KTP with Glinwell explores the application of robotics to agriculture (Amirabdollahian and Koay). In addition, when research impact requiring further development and evidencing was identified, successful applications were made to the central impact grant fund held by the University Research Office for annual grants in the range £4k to £8k to take forward the associated impact plans.

Further engagement with industry resulted from EU and UK grants, including partners from industry in networks, and by commercially exploiting deliverables that result from funded projects. For example, to meet the objective of making the Kaspar robot that provides therapy for children with autism more widely available, a licensing agreement has been signed with the Canadian company, Compusult, to bring Kaspar to market in North America and Asia (as described in the case study *Kaspar the social robot: supporting children with autism and increasing public acceptance of robot-assisted therapy*). Research in the Adaptive Systems Research Group has also informed the development of novel AI algorithms by companies such as Google DeepMind and inspired an international competition to create content for the popular game Minecraft which forms part of the second Impact Case Study, *Designing socially intelligent adaptive systems to inform commercial AI development and engage the public in debates over*

human-robot interaction. Tools resulting from research on automated differentiation have benefitted the oil and gas sector (utility companies such as EDF) and Formula 1 (for optimising aerodynamics), and also have been used in the World Solar Car challenge (https://www.sonnenwagen.org/en/). The impacts are described in the third Impact Case Study, *Automatic Differentiation: faster, more accurate modelling to strengthen risk management in financial services and optimise engineering performance*.

Impact on healthcare and public wellbeing. The Adaptive Systems Research Group has a substantial track record in human-robot interaction and healthcare robotics research, and one of the Unit's strategic priorities is to exploit this research to generate impact on public health and well-being. As described in the impact case study, the Kaspar robot has been used in schools and specialist centres in eight countries and in an NHS Trust, with clear benefits for children with autism spectrum disorder (ASD). Kaspar's effectiveness has also been shown in clinical settings, including a hospital in Macedonia, and in the first feasibility study of the robot in the UK NHS to treat children with ASD funded by a £250k grant from the NIHR. Staff continue to work with the NHS and other partners in healthcare including Nuffield Health, Lister Hospital and Princess Alexandra Hospital to document medical applications of the health care robots in real world environments; joint projects with hospitals span areas such as robotic surgery (Lister), data science and gerontology (Princess Alexandra). The Unit has also contributed to the development of standards in the field of healthcare robotics such as BS EN ISO 13482:2014, the first robot safety requirements for personal care robots, and BS 8611:2016 on the ethical design and application of robotic systems (Amirabdollahian).

Public engagement and outreach. Another aspect of the impact strategy is increasing the visibility of the Unit's research through continued media exposure, and a particular focus is provided by the activities of artists in residence (Dumitriu and May) who generate cultural impact through robotics and biocomputation art works and exhibitions such as *Intelligent Machinery* at the Ugly Duck Gallery in London (2019). Other exhibitions include *Robots* at the London Science Museum, which attracted more than 180,000 visitors in 2017 and received extensive media coverage; for example, on BBC Radio 4 and in The Financial Times, The Guardian and The Telegraph; and exhibitions at the Science and Industry Museum in Manchester, the Life Science Centre in Newcastle, National Museums Scotland, the National Museum of Science and Technology in Stockholm and Hong Kong Science Museum.

Strategic appointments and internal funding. The generation of impact is further supported by staff appointments (such as Koay, Wood, Foerster, Walters) in research areas such as healthcare robotics (including an internally funded Early Career Research Fellowship together with the School of Life and Medical Sciences) and the investment in facilities and equipment such as the Robot House, RoboCup and medical robots, EEG systems together with the cyber security laboratories and equipment (approximately £400k of internal funding support since 2014).

Open Research Environment and Integrity

An important aspect of the Unit's interdisciplinary research is the sharing of research data and tools. The Adaptive Systems and Biocomputation Research Groups make their software publicly available by uploading it onto dedicated GitHub sites. Open access to data such as EMG data (as part of recent publications in Journal of Neuroengineering and Rehabilitation and PLOS One) is provided, and all the Unit's computational models of neural systems on publicly accessible databases such as ModelDB (curated at Yale University) are shared. The Unit is also a long-standing contributor to the Open Source Brain (OSB) Initiative, which is coordinated by collaborators at UCL and which provides access to a rapidly growing number of computational models before publication. To facilitate the sharing and re-use of computational models, an increasing number of the computational models are translated to (or developed in) the simulator independent model representation language NeuroML and staff regularly attend meetings and workshops on model sharing and collaborative model development. A computational model of a cerebellar nucleus neuron that has been developed by the Biocomputation Research Group is the first ever model that is available in NeuroML as well as the two specialist simulators

GENESIS and NEURON, which has led to its use by many laboratories in Europe, Japan and the USA.

The Unit is fully committed to the University's policy to make all research outputs at least Green Open Access, by providing access to outputs through the University Research Archive. An increasing number of outputs are published as Gold Open Access; staff are regular users of the University's Article Processing Fund that provides resources for Gold OA, and the Unit provides additional support for open access publishing from Unit QR funding. The University's Ethics Committee and Intellectual Property and Contract Support team ensure that research follows ethical and legal obligations and standards. The University is a signatory to the Concordat on Research Integrity and there is centrally provided mandatory training on research integrity for all researchers including workshops and an annual seminar in addition to bespoke training on the Doctoral College's Researcher Development Programme in which both staff and research students engage.

Future Strategy

The Unit's future strategy is:

- to focus on Adaptive Systems and Biocomputation as areas for major investment to strengthen research through further strategic appointments of key staff to contribute to both income generation and research impact, including impact on public health and well-being;
- to build on existing strengths in Biocomputation and Adaptive Systems by combining expertise in both areas. For example, combining computational neuroscience and rehabilitation robotics in a project that involves the development of cerebellar models for stroke rehabilitation (in collaboration with Stroke Association and partners at the University of Southampton). This is a timely and important project as the current pandemic increases the risk of stroke whilst at the same time access to stroke rehabilitation in hospitals is more limited due to fears of acquiring COVID-19;
- to fully exploit the new innovation partnership with TWI Hellas to make collaborative research grant applications in partnership with the TWI membership companies with a particular focus on the future Horizon Europe calls to build both research income and further increase economic and social impact (see Income, Section 3);
- to additionally raise the international profile of the Unit by strengthening existing, and developing new, targeted, international collaborations, such as the recent dual award PhD programme with Western Sydney University that currently funds four PhD students on collaborative projects in robotics and neuromorphic computing;
- to further expand and develop interdisciplinary research utilising the University level Research Theme activities and to develop new collaborations with partners from outside computer science;
- to grow and deepen research in the Centre of Data Innovation Research (CoDIR), seeking out new collaborations with partners in industry that involve the application of machine learning and data science to a variety of real-world problems;
- to contribute to a new interdisciplinary Centre for Future Societies Research (CFSR) brought together by the Information and Security Research Theme Champion who is located in the Unit (Amirabdollahian) that combines expertise from computer science with engineering, physics, psychology, law, art and digital media and others to better understand the nature of different societies in the future;
- to take forward the research effort to understand aspects of COVID-19; for example, the Unit has recently joined the Royal Society's Rapid Assistance in Modelling the Pandemic (RAMP) Initiative and the Global Consortium of Chemosensory Researchers (GCCR) that aims to understand the link between COVID-19 and loss of smell.

2. People

The UOA consists of 33 staff (31.2 FTE): seven professors, four readers, 16 lecturers, senior lecturers and principal lecturers together with six research fellows. Eight staff (24%) are Early Career Researchers (ECRs) and the Unit FTE has increased by 14% since REF 2014. The Unit's strategy is to further strengthen areas of existing excellence by appointing talented staff, typically at early or mid-career level, with a proven ability to publish high-quality research outputs and secure research funding. The expectation is that these new staff members will eventually become Readers/Associate Professors and Professors and as a result they have limited teaching commitments in order to help them build their research career.

As well as recruiting new academic staff with leadership potential, postdoctoral research fellows from leading institutions across the world are also recruited. The Unit currently hosts twelve postdoctoral research fellows. Typically, these are supported by external funding, however, as part of the strategy to expand interdisciplinary research (see Section 1) six internally funded Research Fellows (ECRFs and VCRFs) were appointed to strengthen and sustain key research into the future. These, together with the lecturer posts also contributed to a balanced staffing profile, focused towards the sustainability of the Unit. Although the internally funded Research Fellowships are 5-year appointments, the expectation is that they will all move into academic posts within the Unit at the end of this period.

Staff Development

Each new staff member is assigned a senior member of academic staff as a mentor, who provides guidance in terms of publication strategies and funding applications. New staff are also engaged with internally funded PhD students and encouraged to join Research Groups and develop collaborations in order to build up a critical mass. All research fellows and academic staff undergo an annual appraisal and a review of their publication and grant application strategies in order to further enhance their research careers. In addition, they are encouraged to make use of the centrally provided Researcher Development Programme (RDP) and the Doctoral College research student supervisor and examiner training. The RDP includes courses in specialist research skills as well as career development, personal effectiveness, leadership and management. The Unit also provides direct support to both research fellows and staff with significant responsibility for research (as well as PhD students) to attend leading international conferences and workshops using a dedicated £50k budget.

The School of Physics, Engineering and Computer Science provides an excellent support structure for internal promotion facilitated by the University which has an annual academic promotions round. Applications for promotion are prompted as part of the annual appraisal process, and the promotion procedure is explained in regular workshops that are offered centrally by the University. The success of the recruitment and promotions strategy is reflected by four Professorships that have recently been awarded to Polani, Amirabdollahian (both in Adaptive Systems), Schmuker and Steuber (both in Biocomputation) who were all originally appointed as Senior Lecturers and subsequently promoted to Readerships.

Research Students

The 2019 Postgraduate Research Experience Survey (PRES) ranked the University 4th out of 103 universities participating for research culture,15th for supervision and 21st out of 103 for overall student satisfaction. The survey had a 42% participation with over 50,000 respondents nationally, while 62% responded at the University of Hertfordshire, which was positioned in the top quartile for seven out of the eight areas, the other being in the second quartile. At Unit level, research culture was ranked 3rd from 32 computer science submissions and 88% of the postgraduate research students indicated that their supervisors provided helpful feedback and had the required skills and knowledge to support their research, with 92% responding positively that their skills in applying research methodologies and analysing and evaluating results had developed during their programme of studies.

The CCSIR is currently home to 58 postgraduate research students. There is a yearly intake of between 10 and15 students, composed of a mix of both externally funded and self-funded students together with an average of 5 students per year who receive internal university studentships typically supported by QR funding. Given the interdisciplinary character of much of the research in the Unit, the students come from a range of disciplines, including (apart from computer science) mathematics, physics, biology, engineering and medicine. Successful applicants typically have the equivalent of a UK MSc degree with distinction. They are supported by a team of at least two (often three) supervisors having at least two previous successful doctoral supervisions between them.

The progress of the students, and their well-being, is monitored carefully throughout the duration of their doctoral programme. Students have the opportunity to receive detailed feedback from an external assessor during two formal progress assessments at 8 and 18 months (36 months for part time students) after enrolment. These assessments involve the submission of a written report about current progress and planned future work, followed by a viva voce examination, which decides the progression of the students onto the next phase of the PhD programme. The progress and satisfaction of the PhD students are evaluated annually through monitoring feedback and by a dedicated Research Student Tutor. To support monitoring and progression the University has invested in a Research Student Monitoring System (RSMS), an online platform that facilitates the record keeping and interaction between students, supervisors and the University's Doctoral College. Detailed records of all supervision meetings and progression assessments are entered on a regular basis by students and their supervisors into RSMS and are accessible throughout the course of the doctoral study, enabling feedback between students, supervisors and the Doctoral College and providing a robust mechanism to record the students' meetings with supervisors, progress and achievements.

Research students can attend courses as part of the central Researcher Development Programme (RDP) provided by the Doctoral College, which includes training on subjects such as technical writing, statistics and other research methodologies and processes. In addition, they are encouraged to increase their subject knowledge by attending specialist computer science modules at MSc level.

Another important aspect of the education for the Unit's doctoral students is their interaction with leading international experts in their area of research; this is enabled by providing funding for each student to attend several internationally leading conferences (and, when appropriate, specialist international training courses and summer schools such as the EU, Latin American and Okinawa Courses in Computational Neuroscience or the Capo Caccia Workshop towards Neuromorphic Intelligence). The careful selection, training, supervision and positive development of students in the Unit is reflected in their destinations when they leave the University; PhD graduates hold positions at prominent universities, research institutes and companies such as the University of California Los Angeles, the Okinawa Institute of Science and Technology, Microsoft Research and Google.

Equality and Diversity

The School of Physics, Engineering and Computer Science fully supports the University's commitment to all equality and diversity principles. The School successfully obtained the Athena SWAN Bronze award in 2019, is working towards Silver, and maintains an Equality and Diversity (EDIT) working group with diverse members representing academic, professional and research staff and research students. All staff receive mandatory equality and diversity training as part of their general induction, including special training to recognise unconscious bias. The School supports flexible working hours and has since 2014 provided the opportunity for staff to work online from home, when appropriate.

The commitment to equality and diversity is reflected by the success of women at all levels, with 31% of the computer science PhD students, 40% of the lecturers or senior/principal lecturers and 50% of the Readers being women. Until very recently two of the professors were women;

however, one has recently retired and the other has taken up a post to lead a new AI research centre at Waterloo University in Canada. It is planned that both posts will be replaced.

The Unit now has 13.8 FTE or 44% BAME staff compared with 22% in REF 2014. The University is one of only 17 institutions nationally that holds the Race Equality Charter Mark bronze award which it obtained in 2015.

3. Income, infrastructure and facilities

Income

External income for research totalling £8.3M has been obtained by members of the Unit since January 2014. In this period, externally funded research projects have included the Horizon 2020 consortia socSMCs, WiMUST, InTERCoGAM, SECURE, BabyRobot, and more recently projects supported by a variety of British, European and American funding agencies such as Trustworthy Robot Assistants (EPSRC), HRI-BioPsy (US Air Force Office for Scientific Research), a project on neuromorphic engineering (funded by the EU Flagship Human Brain Project), EvoSN (funded by the Polish National Science Centre), a project on odour identification in the mammalian olfactory system (funded by the German Research Organisation DFG) and a NeuroNex award (funded by the MRC and the NSF, USA). Further details regarding these research collaborations are given in Section 4. Other sources of income have included £240k of targeted donations to support the Kaspar robot research project for children with autism from charities and donors such as the Stavros Niarchos Foundation and the John Apthorp Charity.

As indicated in Section 1 under Future Strategy c) the Unit has successfully secured a significant number of substantial EU collaborative grants in Horizon 2020 but these have reduced in number over the last four years as a consequence of the Brexit vote with the growing reluctance of EU partners to consider UK involvement. In order to improve opportunities to engage with the EU in future programmes such as Horizon Europe in August 2020 the University established a formal innovation partnership with TWI Hellas, a wholly owned subsidiary of TWI which has its headquarters in Cambridge. The partnership agreement, that is for 5G Communications, Engineering and Computer Science including all the areas of research in this Unit, facilitates access to over 600 companies who are members of the TWI industrial network to partner in UK and, in particular, EU collaborative funding applications coordinated through TWI Hellas, based in Athens. Two collaborative funding applications to final calls within Horizon 2020 have already been made and it is intended that this partnership will support many further collaborative grant applications with EU partners in the forthcoming REF cycle.

Infrastructure and Facilities

Research in Computer Science is well supported by the University, including technical and administrative support, business and development together with intellectual property support. Individual academic staff and research fellows can apply for small internal grants (up to £10k per person) to develop new interdisciplinary collaborations, explore new ideas and increase the economic and social impact of their research. An annual Capital Expenditure (CAPEX) round has resulted in the creation of several outstanding facilities; these include:

HPC Facility. The University has invested £1800k into a new high-performance computing facility with 2048 cores, several GPUs and five high-memory SMTP machines with 32-48 cores each. The HPC facility is overseen by a management group comprising senior academic staff from computer science, physics and engineering.

Robot House (https://robothouse.herts.ac.uk/). In 2017, the Unit was awarded an EPSRC infrastructure grant (£577k) to upgrade the Robot House (to Robot House 2.0) and designate it a national specialist facility. The Robot House is a residential home that has been purchased by the University and hosts several robots such as a Care-o-bot, a Pepper Robot, a Turtlebot 2 and the telepresence Giraff robot, which are designed to care for people in their homes. It is

managed by a designated Research Coordinator (Holthaus) and a Scientific Manager (Koay) and supported by an annual maintenance grant from the University (currently £20k per annum). Over the last three years a substantial renovation and upgrade was conducted including the installation of a super-fast optical fibre line, which facilitates the involvement of the Robot House in projects such as Digital Twin. This development, which is part of a joint funding application with the online grocer Ocado under the theme of Herts Living Lab, proposes a living lab that supports the delivery of goods from the supplier to the distribution and placement in the Robot House.

In 2020, the Robot House was associated with a successful EPSRC grant application entitled 'Adaptable manipulation skills for unstructured environment' led by the University of Surrey (Guerin) where the team (Amirabdollahian, Holthaus) received £390k. Also, a further EPSRC Network+ application entitled, 'Emergence, tracking fragility, facilitating emergence of healthcare robotics from labs into service with Heriot Watt and Sheffield Hallam Universities' has moved past the outline stage. Other submitted partnered applications include two UKRI Trustworthy Autonomous Systems (TAS) pump priming project applications including the Universities of Southampton, Nottingham and Heriot Watt. These applications support the requirement of the recently completed EPSRC infrastructure grant, that the Robot House be made available to other universities and partners in industry. It has also been used by visitors from the University of Oslo, which has resulted in joint publications in the 14th ACM/IEEE International Conference on Human-Robot Interaction and the International Conference on Robot and Human Interactive Communication (RO-MAN 2019), has inspired a joint grant application with the Japan Advanced Institute of Technology (JAIST) in order to build similar facilities in Japan, and has been put forward in the Horizon 2020 Gatekeeper programme to be adopted as a pilot infrastructure. Finally, it featured on the ITV Tonight programme "Can Robots Save the NHS?" on 27 August 2020, which explored the value of robots as care and assistive tools.

Robotics and Biocomputation Laboratories and Facilities for Research Students and Fellows in the Centre for Computer Science and Informatics Research. All the 58 Computer Science PhD students and 12 postdoctoral research fellows have their own desks and computers in the Centre for Computer Science and Informatics Research (CCSIR), a dedicated building that also hosts human-robot interaction and rehabilitation robotics laboratories. In addition, the RoboCup laboratory, which is situated outside the CCSIR providing access to undergraduate students, contains a robot football arena with Darwin robots, a workshop with 3D printers and dedicated hardware. Achievements of the RoboCup football team include a second place at the World Championships in Brazil (2014), a first place in the Iran Open (2016) and a place in the quarter finals at the World Championships in Japan (2017). The activities of the RoboCup football team, which form an element in the Adaptive Systems case study (see section 1), have generated research impact by stimulating public engagement, for example through exhibitions at the London Science Museum and Barbican Centre. The PhD students and postdoctoral research fellows of the Biocomputation Research Group are housed in the dedicated and well-equipped Royal Society Wolfson Foundation Biocomputation Laboratory, having their own multi-processor machines for high performance simulations (in addition to access to the HPC facility).

Cyber Security Laboratory. The Cyber Security Centre (CSC, founded in 2016) has a dedicated laboratory containing the latest digital forensic toolkits (EnCase, FTK, DFF) and a 64-processor server with 400GB primary memory and 140TB secondary memory to run virtualised infrastructures and create customised testbeds in a dynamic manner. The CSC also has specialised equipment for undertaking research in cyber-surveillance, threat intelligence collection, primary and secondary memory analysis, data recovery, big-data analytics, vulnerability identification and exploit development that includes a GPU server for cryptographic research and a PC3000 kit for recovering data (funded by £350k of internal CAPEX grants from the University). The CSC has performed four penetration tests with companies such as Bulletproof and the Camelot Group and has been awarded the Innovate UK project 'Threat Assessment Model for Information Environments' (TAME) together with the company, Secure Technologies.

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

Research Collaborations and User Partnerships

Research collaborations are strongly supported by the University Research Theme in Information and Security and the CCSIR and CoDIR research centres. Over 60% of research in the Unit involves collaborations with national and international partners in academia and industry. Members of the Adaptive Systems Research Group and the Biocomputation Research Group are involved in a large number of innovative interdisciplinary research collaborations and continue to apply for new ones. Collaborative research projects in Adaptive Systems include:

- SECURE: a collaboration with the University of Hamburg, the University of Plymouth, Fondazione Istituto Italiane di Tecnologia (IIT), Fraunhofer Institut, Telerobot Labs KUKA Roboter GmbH, Honda Research Institute Europe, Ecole Polytechnique Federale Lausanne, Aldebaran Robotics, Cyberbotics that investigates robotic safety in uncertain environments (Unit partners are Dautenhahn and Koay).

- BabyRobot: a Horizon 2020 project that studies child-robot communication and collaboration in typically developing and autistic spectrum children, in collaboration with the Institute of Communication and Computer Systems Athens, Athena Research and Innovation Center (Greece), University of Bielefeld (Germany), KTH Royal Institute of Technology (Sweden), Blue Ocean Robotics (Denmark), Furhat Robotics (Sweden) and the University of Lille (France) (Unit partners Dautenhahn, Robins and Koay).

- HRI-BioPsy: funded by the US Air Force Office of Scientific Research (AFSOR), this project aims to bring together psychological (top-down) and biological (bottom-up) approaches for enhancing human-robot interaction (Unit partners Dautenhahn and Nehaniv).

- A joint EPSRC project with the University of Liverpool and the University of Bristol that studies Trustworthy Robot Assistants (Unit partners Dautenhahn and Amirabdollahian).

- socSMCs: a Horizon 2020 project that intends to develop measures for various levels of multi-agent entrainment (together with KTH Royal Institute of Technology in Sweden, the Universities of Osnabrück and Hannover and White Matter Labs in Germany, and University Pompeu Fabre Barcelona and PAL Robotics in Spain, Unit partner is Polani).

- WiMUST: a Horizon 2020 project that involves a collaboration with partners in Italy (UNIGE-ISME, Graal Tech), Portugal (IST-ID, Geosurveys), Germany (Evologics), France (CGG) and the Netherlands (Geomarine Survey) in order to study strategies for swarms of autonomous underwater surveillance vehicles (Unit partner Polani).

- InTERCoGam: sponsored by an individual Horizon 2020 fellowship to Salge, this project includes a research visit to New York University to investigate the use of information theory for the evaluation of content generation in computer games.

- A collaboration with BMW on multi-agent reinforcement learning (Unit partner Salge).

Members of the Biocomputation Group are also involved in many interdisciplinary projects with partners around the world, for example:

- NeuroNex From Odor to Action: Discovering Principles of Olfactory-Guided Natural Behaviour: a collaborative project with UC Boulder, Caltech, Yale, Salk Institute, Scripps Institute, Penn State University, Weill Cornell University, Duke University, NYU School of Medicine, University of Pittsburgh, University of Utah, Arizona State University, Lehigh University (all USA), McGill University (Canada) and the Francis Crick Institute (UK) that aims to investigate how nervous systems sense and process olfactory stimuli (funded by the US NSF and the MRC, Unit partner Schmuker).

- EvoSN: a joint project with Adam Mickiewics University (Poznan, Poland) that uses evolutionary optimisation to develop spiking neural networks for different computational tasks and robot control (funded by the Polish National Science Center, Unit partner Steuber).

- A project that is funded by the German National Research Agency (DFG), with the aim to understand neuronal mechanisms of complex odour identification in the mammalian olfactory system (Unit partner Steuber).

- A collaboration with Erasmus Medical Center Rotterdam that studies mechanisms underlying the generation of epileptic absence seizures and develops techniques to terminate the seizures (Unit partner Steuber).

- Joint work with the Max Planck Institute for Chemical Ecology (Jena, Germany) and Örebro University (Sweden) that involves data analysis, signal processing and computational modelling in insect and robot olfaction (Unit partner Schmuker).

- Work in neuromorphic computation that forms part of the EU Flagship Human Brain Project (Schmuker). The University has recently joined the HBP (coordinated by the Ecole Polytechnique Federal Lausanne Switzerland) as partner 118.

- An ongoing collaboration with the University of California Berkeley, University of Debrecen and Rényi Institute (Hungary), University of Passau (Germany) and University of Dundee to disseminate and exploit the results of the recently finished BIOMICS project through an open-source software framework (Unit partner Nehaniv).

- A collaboration with University of St Andrews, University of Western Sydney (Australia) and Akita University (Japan) on the application of Krohn-Rhodes theory and permutation groups, with applications to systems biology, physics and artificial intelligence (Unit partner Nehaniv).

- Work with the Institute of Psychiatry, Psychology and Neuroscience, Kings College London to study applications of computational complexity measures to the analysis of EEG data (Unit partner Nehaniv).

- The Global Consortium of Chemosensory Researchers (GCCR), a collaboration to understand the link between COVID-19 and olfaction/olfactory loss (Unit partner Schmuker).

Partnerships with industry include the contribution of the COMPAD programme to the development of STCE software tools for computational engineering (with NAG Oxford and RTW Aachen, Christianson) and KTP projects that involve a local company from the space industry (Kirner, £170k), the application of machine learning and data mining to automated negotiation (Helian, £226k), speech analysis (Sun, £224k), diagnostics for operational health (Sun, £171k) and pharmacology (Helian, £131k) and the application of robotics in agriculture (Amirabdollahian and Koay, £258k). Another project at the interface between computer science and agriculture is funded by Rothamsted's Agri-Tech Research Innovation Accelerator (AgRIA) programme and involves data analysis for model-based decision support for farmers (Schmuker, £51k).

Contributions to Economy and Society

The Unit's strategy is to increase the visibility of its research through continued outreach and media exposure. Research is regularly presented at high-profile events such as the IBM Think Summit London (Polani), Le Monde Festival Paris (Cañamero), the Festival Puerto de Ideas Chile (Cañamero), the Times Cheltenham Science Festival (Dautenhahn), the Women in Machine Intelligence Dinner (Dautenhahn), the Celebrating Women in Technology event for sixth formers (Dautenhahn), the British Computer Society Ada Lovelace Day (Dautenhahn), the Tabakalera Festival in San Sebastian (Cañamero), the Frankenstein Festival at the London Science Museum (Cañamero), the "Evolution or Revolution" exhibition about the changing world of work at the London Science Museum (Dautenhahn), the "Feeling Emotional" Friday Late Event at the Wellcome Collection (Cañamero), the Re-work Workshop on The Future of

Education (Cañamero) and the German Public Technology and Entertainment Conference TEDxBodensee (Schmuker).

The Unit's robotics research continues to provoke media interest and stimulate public discussion, with recent interviews on BBC News, BBC Radio 3 and 4 (Dautenhahn, Cañamero, Polani), in Le Monde (Cañamero) and in the New York Times (Cañamero). Work by Salge on applying AI to the popular computer game Minecraft has featured in MIT Technology Review and AI in Games (more than 50,000 views). Other means of communication include the University's research blog, articles in The Conversation (Polani, Nehaniv, Vidalis, Abouzakhar), which in turn often lead to further interest from the media (for example BBC News Arabic, Abouzakhar), and the publication of books about topics of general interest such as the use of social media in China (Che). Unit research features regularly at events that are organised by the University and open to the general public, for example the Innovation Showcase (Dautenhahn, Cañamero, Jones, Steuber), the Public Engagement Conference (Cañamero), the Women in STEMM Network Event (Cañamero) and the East of England Big Bang Fair that was hosted by the University in July 2018 (Dautenhahn, Cañamero, Jones, Walters, Koay).

Another route to contribute to society is provided by the Unit's Artists in Residence programme that explores the relationship with digital technology from an artistic point of view, provoking substantial public discussion; and further economic and societal contributions stem from the Unit's close collaboration with partners in industry and organisations such as the local Chamber of Commerce, various police forces and the NHS.

Contributions to Sustainability of Discipline

Members of the CCSIR contribute to the Computer Science research base by providing services to the discipline as follows.

Journal editing: members of the Unit act as founding editor in chief of the journal Interaction Studies – Social Behaviour and Communication in Biological and Artificial Systems (Dautenhahn), as topic editor in chief of the International Journal of Advanced Robotics Systems (Nehaniv), and as editor, associate editor or guest editor of the following journals: Journal of Autonomous Agents and Multi-agent Systems (Polani), PLOS Computational Biology (Polani, Steuber), Cognitive Systems Research (Cañamero), Journal of Artificial Intelligence and Consciousness (Polani), Electronics (Kirner), Adaptive Behaviour (Dautenhahn), Journal of Rehabilitation and Assistive Technologies Engineering (Amirabdollahian), International Journal of Social Robotics (Dautenhahn), IEEE Transactions on Cognitive and Developmental Systems (Dautenhahn, Nehaniv), IEEE Transaction on Affective Computing (Dautenhahn), Biosystems (Nehaniv), Interaction Studies (Cañamero), Frontiers in Neuroinformatics (Steuber), Frontiers in Systems Neuroscience (Steuber), Frontiers in Neurorobotics (Cañamero), Frontiers in Evolutionary Robotics (Cañamero), Interaction Studies (Cañamero), Paladyn Journal of Behavioural Robotics (Amirabdollahian, Polani), Optimization Methods and Software (Christianson), Research Ideas and Outcomes (Schmuker), Frontiers in Neuromorphic Engineering (Schmuker), Frontiers in Artificial Intelligence and Robotics (Schmuker, Polani, Cañamero), Computational Intelligence and Neuroscience (Schmuker), Advances in Complex Systems (Polani), Scientific Programming (Kirner), Journal of Digital Forensics Security and Law (Jones), Computers and Security (Jones), Information and Computer Security (Jones) and the International Journal for Learning Technology (Jefferies). Other editorships include roles as editor of the book series Advances in Interaction Studies (Dautenhahn) and section editor of the Springer Encyclopedia of Computational Neuroscience (Steuber).

Conference convening: Unit staff have co-organised / are co-organising international workshops and symposia such as the workshop on "Insights Gained From Detailed Dendritic Modelling" at the Annual Computational Neuroscience Meeting CNS*2018 in Seattle, USA (Steuber), the special track "IoT and Cyber-Physical Systems and Applications" at the 2nd IEEE Conference on Societal Automation SAC 2020 (Kirner), the special track "Mixed Criticality Systems" at the 1st International Conference on Event-Based Control, Communication and Signal Processing EBCCSP 2015 (Kirner), the 11th International Conference on Social Robotics,

Madrid 2019 (Cañamero), the special session on “Emotion and Affective Technologies for Inclusive Mental Health”, Cambridge 2019 (Cañamero), the 1st International Workshop on Architectures and Evaluation for Generality, Autonomy and Progress in AI, Stockholm 2018 (Cañamero), the workshop “Empathic Human-Robot Interactions” at the European Robotics Forum 2017, Edinburgh (Dautenhahn), the workshop “Towards reproducible HRI experiments: scientific endeavors, benchmarking and standardization” at the HRI 2017 conference, Vienna (Dautenhahn), the Third and Fourth international symposia on New Frontiers in Human-Robot Interaction, London 2014 and Canterbury 2015 (Dautenhahn), the multi-disciplinary workshop “Emotions as feedback signals” held in 2016 at the Lorentz Center in Leiden (Cañamero), the TRUCE workshop on Information in Decision Making with invited participants at the University of Hertfordshire in 2015 (Polani), a special session on Quantifying Embodiment at the European Conference on Artificial Life 2015 (Polani), a workshop on Information-theoretic Incentives for Artificial Life at Artificial Life 2014 New York (Polani), the annual International Workshop on Security Protocols, Trinity College Cambridge (Christianson), workshops on Robotics for Movement Rehabilitation and Natural Interaction with Social Robots at the European Robotics Forum Rovereto 2014 (Polani, Dautenhahn). Other roles include programme chair of the IEEE Symposium on Artificial Life 2015 and 2017 (Nehaniv), panel chair at the International Conference on Availability, Reliability and Security 2016, Salzburg (Jones), proceedings chair at EASE 2016-2018 (Bowes), co-chair at the ALT Conference 2015, Manchester and the 14th European Conference on E-Learning 2015 at the University of Hertfordshire (Jefferies), co-chair of the 9th workshop on Guided Self-Organisation 2018, Leipzig (Polani) and programme chair of RO-MAN 2014 and ICORR 2017 (Amirabdollahian).

Keynote talks and invited presentations: members of the Unit regularly give keynote presentations at conferences and workshops such as the Gordon Research Conference on the cerebellum in Lewiston, Maine, USA 2021 (Steuber), the 15th Annual ACM/IEEE Conference on Human-Robot Interaction, Cambridge 2020 (Cañamero), the 29th Annual Computational Neuroscience Meeting CNS*2020 online (Polani), the 11th International Conference on Social Robotics, Madrid 2019 (Cañamero), the 7th Cambridge Neuroscience Symposium 2019 (Cañamero), the Conference of the International Society for Research on Emotions, Amsterdam 2019 (Cañamero), the Bernstein Workshop on Multi-level Modelling and Simulation, Göttingen 2018 (Steuber), the workshop on Causation, Information and Autonomy, Madison 2019 (Polani), the workshop on New Advances in Biocomplexity, Sydney 2019 (Polani), the NeurIPS workshop on Machine Learning Challenges “in the Wild”, Montreal 2018 (Polani), the International Conference on Promising Electronic Technology, Gaza City 2019 (Kirner), the International Symposium on Accelerating Biology, Pune, India 2016 and 2017 (Kim), the Crop Modelling and Precision Agriculture Workshop, Passo Fundo, Brazil 2015 (Kim), the First Latin American Conference on Plant Phenotyping, Talca, Chile 2015 (Kim), the JSSR 2016 Symposium on Social Robotics, Abu Dhabi (Robins), the Google Panel on Technology and Disabilities, London 2016 (Robins), the 6th International Conference on Disabilities, Tel Aviv 2015 (Robins), the interdisciplinary workshop “Connecting Minds”, Leiden 2016 (Cañamero), the IEEE/RSJ International Conference on Intelligent Robots and Systems, Hamburg 2015 (Cañamero), the Robo Philosophy Workshop “Artificial Empathy” Aarhus 2016 (Cañamero), the 3rd workshop on Child-Robot Interaction, Vienna 2017 (Dautenhahn), the International Conference on Multimodal Interaction, Seattle 2015 (Dautenhahn), the IEEE ICDL-EPIROB Conference, Brown University 2015 (Dautenhahn), the Summer School on Neurorehabilitation, Greifswald 2014 (Dautenhahn), the Latin American School on Computational Neuroscience, Natal 2014 and Sao Paulo 2016, 2018 and 2020 (Steuber), the Workshop on Statistical Physics, Information Processing and Biology, Santa Fe Institute 2016 (Polani), the conference on Information, Control and Learning, Jerusalem 2016 (Polani), the Barcelona Cognition, Brain and Technology Summer School, 2016 (Polani), the NIPS 2014 workshop on Autonomously Learning Robots (Polani), the RO-MAN workshop on Novel Patient-Robot Interfaces, Edinburgh 2014 (Amirabdollahian), the conference “Delivering Housing Solutions for Older People: Ageing Well at Home, Stratford 2014 (Amirabdollahian), the Human Brain Project Summit, Heidelberg 2014 (Schmuker).

Elected international posts and other memberships: President of RoboCup Federation 2017-19 (Polani); President of the international Organisation for Computational Neurosciences OCNS,

2019-22 (Steuber); Membership of EPSRC Peer Review College (Polani, Dautenhahn); Membership of the ACM Distinguished Speakers Program (Dautenhahn); Senior Membership of IEEE (Shafarenko, Nehaniv, Dautenhahn)

Committees and taskforces: the following are highlighted among many programme committee memberships: the NEUROTECH Consortium that coordinates and supports the European neuromorphic computing technology community (Schmuker), the IEEE RO-MAN Standing Steering Committee (Dautenhahn), the IEEE/CIS taskforce on artificial life and complex adaptive systems (chaired by Nehaniv), UK taskforce for robotic standardisation (Amirabdollahian), Board of Trustees of the RoboCup Federation (Polani), HiPEAC network of excellence in High Performance Computing (Shafarenko), IFIP Working Group 10.3 'Concurrent Systems' (Shafarenko), RESG Executive Committee of the BCS (Veneziano), Multi-scale Computational Neuroscience Working Group of the National Institutes of Health USA (Steuber), Scientific Committee of the Latin American School on Computational Neuroscience (Steuber), Executive Committee of the Organization for Computational Neurosciences (Steuber), the Advanced Programming Specialist Group of the British Computer Society (Kim) and the technical committee of the International Society for Olfaction and Electronic Nose (Schmuker).