Institution: University of Greenwich

Unit of Assessment: 11 - Computer Science & Informatics

1. Unit context and structure, research and impact strategy

a. Overview
Our UoA11 submission is hosted in the School of Computing and Mathematical Sciences, which was formed in 2018 through a merger between the Departments of Computing and Information Systems and the Department of Mathematical Sciences. Since our REF2014 submission the School has seen a global restructuring in all its activities, and a redefinition of its research strategy to better align with the evolution of the discipline and to refocus, as well as develop, its research base.

In line with the overall University research strategy, UoA11 aims to develop sustainable research on a selected number of topics, which can also inform other activities in the School, in particular Teaching and Enterprise. The majority of the research activity can be categorised as applied research, with some more fundamental work on basic Machine Learning techniques (e.g. categorization and unsupervised learning). Underpinning this evolution has been the appointment of 13 new staff, such that during the REF period, the unit has seen an increase in FTE from 14 to 18.8. There is now little overlap with the previous submission.

The heart of the revised research strategy is now to focus on Computer Science rather than Computational Engineering which has been consolidated into our UoA12 submission. Significant investment has taken place to develop Computer Science research, primarily around Cybersecurity, the Internet of Things and more recently, Artificial Intelligence and Data Science. Therefore, since 2014:

- two groups have been disbanded (eCentre and CCCS)
- three new groups have been formed (ISEC, CSIG and AI & DS)
- three groups operating in the field of Computational Engineering have been incorporated into UoA12 (FSEG, CMRG, CSEG).

However, in view of the fact that several FTE from the FSEG group were submitted as part of REF2014, one of our Impact Case Studies still originates from that group.

In addition to central university support from Greenwich Research and Enterprise (GRE) and the Research and Enterprise Training Institute (RETI), the UoA is supported at faculty level through the Faculty R&E Support Team (FRES), which has 9 FTE to support research and enterprise across the faculty. This team includes a Research Development Officer (RDO) and Enterprise Development Manager (EDM) and staff that provide research group support, PGR support, event co-ordination, and project and budget management support.

b. Unit Composition and Changes since REF 2014
The Centre for Computer & Computational Science (CCCS), which was the largest group in our REF2014 submission, included a broad mix of activities in Cybersecurity, optimisation and Artificial Intelligence (AI) and spatial informatics. For the current reporting period, we have realigned these activities into three specific groups which now constitute the structure of our UoA11 submission: a cybersecurity group (ISEC), a spatial informatics group (CSIG), and most recently (2020), an AI & Data Science group. These groups have received significant investment in the form of new staff appointments, and have developed through the acquisition of external funding.

Finally, the current submission has integrated colleagues previously returned under UoA10 (Alan Soper, Vitaly Strusevitch) whose work in operations research and scheduling bears relevance to UoA11 and is related to other AI work, e.g. Planning. In addition, two staff members (Neil Saunders and Kayvan Nejabati Zenouz) are included in this submission with their outputs being

cross-referred to UoA10. It should be noted however, that their background also includes Data Science, computing applications and specific work undertaken as part of their main specialisms (Algebra, Topology) applications in machine learning, as well as quantum computing.

c. Impact Strategy

Our pathway to impact is further informed by a mid-term strategy that was put in place to translate the Unit's research expertise to industry innovation in the form of technology and knowledge transfer. As such, research results are integrated into Enterprise activity through the participation of key grant-holder academics in KTP, KEEP+ and Innovate UK proposals. Examples of recent activity are two KEEP+ projects (Mohammad Majid Al-Rifaie in 2019; Muhammad Taimoor Khan in 2020) one of which has been extended to a KTP proposal to be submitted with the industry collaborator (ReapSource). Along the same impact strategy, other staff from this UoA (Hai Huang, Alan Soper, Kayvan Nejabati Zenouz) are incorporated in two KTP proposals as co-investigators to develop advanced intelligent data analytics and visualisation for the industry collaborator (Railsbank). Our Enterprise expansion strategy has developed from our established core of KTP projects within UoA11, which also generates substantial contribution to the potential Impact Case Studies related to them. In total, 10 staff are PI or CI in KTP projects or other forms of Innovate UK funding.

This submission reflects a research strategy which has been substantially revised, with new research areas being at different stages of their development and having reached various levels of maturity. For instance, considerable progress has been achieved in the field of Cybersecurity since REF2014, which in particular has attracted significant and sustained external funding over the reporting period, totalling £2.3M (although some of these grants extend beyond the current census date). Artificial Intelligence and Data Science activity being the latest addition, it is still in its early stage of development, with a strong contingent of Early Career Researchers. However, it rests on a very solid foundation of recent results and outputs in high-profile venues (IJCAI, AAAI etc.), some even already highly cited (for example, the following paper has received in excess of 500 citations on Google Scholar: Wang, X., Cui, P., Wang, J., Pei, J., Zhu, W. and Yang, S., 2017, February. Community preserving network embedding. In *AAAI* (Vol. 17, No. 10.5555, pp. 3298239-3298270).

d. Fraction of outputs submitted under portability rules

With the significant investment in research active staff over the past three years, a substantial number of their recent research outputs have become available, which results in almost 50% of our total outputs being submitted under portability rules. Despite the significant contribution of portability to our submission, we are confident in the sustainability of this published research, in particular if we consider the performance of recently appointed staff in publishing similar outputs to those transferred under portability, since they have joined Greenwich. Over the past year alone, 5 staff who have contributed outputs to the current submission under portability rules have since published, with a Greenwich affiliation, in similar venues to their portable outputs: IJCAI, AAAI, AAMAS, IEEE Internet of Things, IEEE Transactions on Industrial Informatics, and the International Journal of Computer Vision (IJCV). Another consequence of the high level of output portability is that a few additional topics that are peripheral to the above described research strategy are represented through several outputs, primarily in Human-Computer Interaction.

e. Research Groups

Internet of Things and Security Research Centre (ISEC)
The Internet of Things and Security Research Centre (ISEC) carries out research on security and privacy technologies for distributed digital environments where a security breach in cyber space can affect people and systems in physical space, from smart homes and smart buildings to robotics and industry 4.0. It was founded in 2018 out of members of its predecessor, the Centre for Security, Auditing and Forensics Education as well as other academic staff in

computer science with a track record in cyber security and privacy. It was strengthened with new academic staff recruited externally (Emmanouil Panaousis, Taimoor Khan and Ivana Tomic).

Since 2014, the University has invested in 6 new appointments related to Internet of Things (IoT) and security, including Associate Professors, Senior Lecturers and Lecturers from top research institutions. Out of the current 11 FTE members of ISEC, three have joined from Imperial College, two from the University of Surrey, and one from UCL. These have been strategic appointments with the purpose of enriching the theoretical grounding of the department's cyber security research, especially in formal methods, control theory and optimisation in IoT security. In addition, there have been eight more postdoc research fellows (up from 1 in the previous REF period), nine more PhD students (up from 4) and a total of four PhD completions (up from 0). One more Senior Lecturer is currently being recruited.

ISEC membership brings expertise in embedded system security, mathematical modelling, formal methods, optimisation and machine learning together with practitioner skills in penetration testing and digital forensics. The Centre's research strategy prioritises multidisciplinary research and the validation of theoretical grounding with laboratory and in-the-wild experimentation with end-users. The emphasis on real-world implementation has helped generate collaboration with industrial partners (in total, 21 companies, including Fiat, Caixa Bank, HPE, IBM and others) across eight of the Centre's ten externally funded research projects. ISEC is taking measures to ensure the sustainability of its research income post-Brexit through diversification of the funding bodies targeted. For instance, ISEC will continue building on its existing track record with grants from the EPSRC, NCSC, the MoD and the British Council.

ISEC's impact strategy starts with the selection of research areas that have clear and increasing potential for industrial and societal impact. Its research relates to tackling the cyber security and privacy challenges introduced by the increasing dependence on internet-connected physical devices as part of digital transformation in the industry, working from home, e-commerce and communication over social media. These areas have now become even more important because of the societal and work pattern changes accelerated by the Covid-19 pandemic. After this impact-based selection of research areas, each project is monitored in terms of its potential for exploitation. In support of this strategy, the Head of ISEC has the role of impact champion, emphasising the importance of impact to its members, helping shape each project's impact plan and sign-posting impact opportunities for each project. In addition, the Centre has an enterprise lead (Emmanouil Panaousis), who is promoting its research to companies in the sector through attendance at industry cluster meetings and one-to-one meetings with key industry players.

Under this direction, ISEC has taken the first steps for deployment and evaluation of its technologies by industrial partners within its research projects. Some first examples include the evaluation of our proprietary cyber security investments software by healthcare organisations (project CUREX), the integration of our cyber security computation offloading tool MEDICI in FIAT's smart manufacturing environment (project C4IIoT) and the deployment of our information trustworthiness toolkit on the Blasting News digital news platform (project EUNOMIA). These will be followed in project CHAI with a new security service for smart home AI company Gas Tag, a cyber hygiene training programme with cyber security training provider Bob's Business and a cyber-physical security monitoring system for e-commerce multinational SONAE in project ENSURESEC. Having built a robust base of research output with medium to high technology readiness through pilot research projects, the impact activities planned include a cyber investment decision support product for SMEs to be commercialised through a spin-off company, as well as two new commercial training programmes, one in smart home privacy powered by a mobile Augmented Reality (AR) application currently supported by the University's enterprise fund, and one in information hygiene for social media users in partnership with Trilateral Research and SYNYO. In addition, a series of Innovate UK knowledge transfer partnership bids are planned, with the first bid currently being submitted in collaboration with the UK Government Cyber Essentials programme partner, IASME.

ISEC prioritises the opportunities for its members to grow their profile rapidly. All research grant applications involve at least one junior member of the group as co-investigator, with the expectation that the experience gained is then utilised by them leading their own grant applications. This strategy was successful in submitting and being awarded projects H2020 C4IIoT and H2020 ENSURESEC. At the same time, it ensures continuity of each corresponding research theme should a principal investigator leave the University. In addition, the group aims to help its PhD students in progressing academically as independent researchers or to secure strong positions in the industry. There have been four PhD completions in cyber security since 2014. These PhD graduates have since moved to postdoctoral and lecturer positions at the University, and one to a senior IoT Security position in industry (Splunk).

ISEC's upward trajectory is evident in the volume of research publications in cyber security, with an output of 51 journal articles, 49 conference publications, 4 book chapters and 2 books. This is compared to 4 journal articles, 14 conference publications and 1 book chapter for research in Cybersecurity submitted to REF2014. 53% of these publications were in collaboration with external institutions. In addition, ISEC encourages interdisciplinary collaboration shown by 14% of its publications being in collaboration with partners from different disciplines. Indicative external examples include psychologists, neuroscientists and education theorists in EPSRC projects Cocoon and CHAI; criminologists and law researchers in H2020 TRILLION; computational social scientists and communication scientists in H2020 EUNOMIA; economists in NCSC MERIT, as well as physicists in joint PhD supervision and publications. Where possible, ISEC's research is published in Gold open access journals (14 in the 2014-2020 period), its code is provided in open-source format on GitHub, and its datasets are provided on OpenAIRE.

This upward trajectory also manifests itself through a significant increase in the acquisition of research funding, which has seen a 13-fold increase in cyber security funded proposals since REF2014 (£170K and 2 successful awards).

Centre for Spatial Informatics at Greenwich (CSIG)
The Centre for Spatial Informatics at Greenwich (CSIG) grew out of the Greenwich GIS Research Group (g^3) and focuses on the informatic aspects of geographic information science. Aspects covered by the research include fundamental theory, modelling, and human spatial cognition. The core members of the Centre are academic staff and students at Greenwich who have expertise in the disciplines of computer science, mathematics and geographic information science. The group also has links to the Ordnance Survey, and other geospatial-related organisations and companies. Areas of particular focus include: computational and cognitive aspects of pedestrian navigation particularly related to smart cities; theoretical studies of rich spatial relations, collective behaviour and movement pattern analysis with applications in smart cities, transportation, urban planning and the digital economy.

The Centre has been led by Professor Mike Worboys with Dr Zena Wood as his deputy (January 2014 – April 2019). Prof. Worboys has 20 years of experience in leadership roles, being Head of the Department of Computer Science at the University of Keele, and Director of the School of Computing and Information Science, University of Maine, USA.

During the reporting period, the Centre hosted three academic staff and currently has two research students and one early-career researcher.

Artificial Intelligence and Data Science
This newly established research group was formed towards the very end of the census period (2020) and reflects new investment in a key area of computer science, which was insufficiently represented in the School. It comprises of nine staff who have been appointed during the current REF cycle, including three since 2019, and a further two after the census period. It has the highest proportion of ECRs in the UoA, with two-thirds of its members qualifying, and will soon host 50% of the School's research-active staff relevant to UoA11.

These appointments have also been coordinated in terms of AI topics and respond to an overall strategic aim to i) strengthen applied research in Machine Learning (ML); ii) retain an activity in symbolic AI, primarily search, planning and semantic web; iii) develop capability in some fundamental ML techniques, and iv) integrating work from Mathematics, in particular time series analysis and Bayesian statistics.

Newly appointed members of the group have published, over the reporting period, a total of 13 papers in major venues such as IJCAI, AAAI, ECAI and the International Journal of Computer Vision (IJCV), several of which are part of the Unit's submission under portability rules. However, since joining Greenwich, several new staff have had new outputs published at IJCAI, AAAI and in IJCV.

The number of research topics is commensurate to the size of the group, and their distribution demonstrates the balance between symbolic AI and ML, as well as between fundamental techniques and applied AI work:
- Search and planning: non-admissible search, planning domains acquisition, route planning for GIS and Unmanned Aerial Vehicle (UAV)
- Unsupervised learning techniques: Nonnegative Matrix Factorisation (NMF), subspace clustering
- Deep Learning applications: computer vision for face expression recognition and generation, autoencoders for plan-like sequence generation

Due to its recent establishment (2020), the Group has not yet acquired external research funding. Its funding strategy will capitalise on the strategic importance of its subject and will target Innovate UK initiatives, Horizon Europe and EPSRC, in particular through the new investigator scheme. Target application areas include Health (imaging, neuroscience), AI Ethics, UAV control, information access and eCommerce, and computer games. The group will also investigate synergies with other subjects, including Cybersecurity and Geographical Information Systems.

In terms of central investment from the University, the Group has already been supported through the procurement of specialist hardware supporting Deep Learning research. Moreover, the University intends to dedicate a significant fraction (up to 33%) of any future UoA11 QR funding to sustaining the early stages of its development.

f. Five-Year Research Plan
The reporting period has seen a major transition in the nature and scope of the research conducted, as well as the organisation in terms of research groupings. These have been driven by a combination of factors, some external, such as recent developments of Computing as a subject (at all levels: teaching, enterprise and research); the evolution of research topics at the international level; and some internal, such as the School's demographics and staff turnover.

Over the next 5 years, our strategy will be articulated around four core objectives, aiming at maintaining excellence in a limited number of selected areas:

- **Consolidating the new research structure around the two main research groups** - We expect to consolidate this new organisation by fine-tuning group structure and membership. The two main groups already have different levels of maturity. ISEC already enjoys an appropriate hierarchical structure, with several staff operating as PI for external funding, and being able to mentor or advise junior staff. One objective will consist in ensuring that external funding is sustainable through a diversification of funding sources. AI & Data Science is primarily staffed with ECRs, who will need to be developed from independent researchers to PI's on grants of increasing value, with support from more senior staff and expansion in the number of PhD students supervised. Due to commonality of topics (e.g. spatial data science and route planning), CSIG will likely be reincorporated into AI & Data Science. This will lead to a re-examination of whether sub-groups need to be defined on the basis of application areas. Another consideration for

sub-groups is that a number of staff, including some appointed after the census date, are active at the intersection of the main group's topics of interactive systems or media. Finally, synergies between the groups will be considered on a case-by-case basis, for instance in the use of AI techniques for Cybersecurity.

- **Strengthening the pathway to impact -** Impact case studies follow a lifecycle dependent on the group's years of operation and a specific effort will be dedicated to ensure that our two new groups are in a position to generate significant impact by the next REF cycle. Intended measures include: follow-up grants of a more applied nature (including KTP and knowledge exchange mechanisms) improving take-up of research results; considerations on patenting and licensing specific software, or release it as open source where appropriate; and contribution to standards, in particular in the field of cybersecurity. Impact based on societal contribution will be considered in the area of health applications of AI, or AI ethics (for instance, in conjunction with affective computing).

- **Developing and retaining the current staff base** - Both Cybersecurity and AI & Data Science are areas facing significant shortage of expertise in both academia and the private sector and, as a consequence, staff retention and development will constitute an essential component of our research strategy. In addition to existing mechanisms supporting generic staff development, we aim to continue developing an attractive environment in terms of opportunities for PhD supervision as well as infrastructure, in particular the provision for HPC in relation to AI and Machine Learning, whether in the School or through central University provision. In terms of bespoke staff development, the strategy will capitalise on previous actions: the UoA has benefitted from a significant staff development budget, which has proven essential in allowing researchers to extend their practical skills in programming languages, specialist software such as graph databases, Cybersecurity certifications, and deployment of AI techniques for the Internet of Things.

- **Ensuring consistency of research topics within each area** - The appointment of a significant proportion of new staff from various national and international institutions has revitalised research in the Unit, but inevitably raises issues on the number and consistency of research interests. In the field of Cybersecurity, consolidation has taken place through the acquisition of new externally-funded projects which have brought together several new members, this has helped in focussing research topics even beyond existing grants. Similar work will have to take place within the recently-formed AI & Data Science group, in particular in terms of balance between the technical and the applicative topics. In the first instance, this will be primed by the next enrolments of PhD students

2. People

a. Staffing and staff development strategy
There have been considerable staff changes beyond the creation of the School from the previous Departments of Computer and Information Science and Mathematics. Some of these changes have been dictated by a change in research focus and strategy, including significant recruitment of new staff, and some by the School demographics, career evolution and personal circumstances.

Of the nineteen staff included, only three were part of our REF2014 UoA11 submission and two were part of our UoA10 submission. The number of senior researchers remains comparable (4 professors, 2 associate professors) however the submission contains a significant fraction of Early Career Researchers, in particular in the newly formed Artificial Intelligence and Data Science group.

The staffing strategy has been focussed on the recruitment of new staff, primarily in Cybersecurity and Artificial Intelligence, with staff joining from INRIA (France), the University of Tokyo (2), Imperial College (2) and the University of Surrey (2). Moreover, a number of staff returned to REF2014 have opted for phased retirement or a change of career pathways and, as a consequence have not met the test for Significant Responsibility for Research (SRR).

An essential part of our People Strategy consists in ensuring that significant responsibility for research is properly supported in terms of workload, as reflected in the University's workload management model, or its equivalence in TRAC reporting. Workloading of Research activities can be considered under two main categories of funded *vs.* internally funded (or "investment"), research time allocations. The former corresponds to external funding via research grants as well as Faculty or University funding (including via the use of QR funding), while the latter draws from the hosting School's internal budget. This is of particular significance for our UoA11 submission, as 100% of staff returned have standard academic contracts, none of which are QR-funded.

The University operates a number of competitive funding schemes to support researchers at various stages of their careers. A sabbatical scheme is managed at Faculty level, during which staff are relieved from any teaching-related duty for a full academic term. Four staff returned to UoA11 (20% of staff returned) have benefitted from this scheme over the reporting period. Various schemes provide seedling funds for ECRs (funding equipment, staff time or research assistants), equipment, or support for research exchanges (visiting researchers or research stays).

The majority of grants awarded to the UoA (Research Councils, H2020) include provisions for PI or Co-I to have their time charged to the project. The School ensures that staff who are awarded external funding as PI see this appropriately reflected in their workload, for instance by monitoring total workload and providing additional support where needed.

Moreover, whenever a PI charges for their time in grant applications, they receive a matching workload allowance corresponding to 100% of the time charged. This additional research time ensures that PI involvement is not limited to project management, or can also account for future grant preparation and bidding. This allowance somehow bridges the gap between funded and investment research allocations.

Newly appointed staff benefit from a reduced teaching load as part of our University workloading model, which operates by capping frontline teaching to 40% during term times for their full first twelve months: the policy explicitly mentioning "development of research" as a rationale and this allowance is clearly distinct from other onboarding allowances or new material preparation ones, which are subject to separate arrangements. This policy is of particular benefit to Early Career Researchers (ECR): however, it applies to all staff irrespective of their career stage or academic grade.

Staff on the research career pathway receive supplemental research allowances whose magnitude can vary based on previous years' performance, primarily measured through research outputs. Research output quality is measured through a combination of peer review, indicators (CORE ranking) and metrics (ScimagoJR and Google Scholar citations). This measure of quality is designed to avoid excessively formulaic approaches, but to ensure that publication in leading venues for which there is strong subject consensus is properly supported.

Finally, research group leaders also receive a research allowance corresponding to 10-15% of their total workload.

In total, these additional ("investment") allowances can be estimated to 3+ FTE per year over the past three years.

Early Career Researchers are supported through a variety of mechanisms which address workload, training, and mentoring. In addition to the quantitative aspects of workload, which limits teaching in their first year of employment; there is also a qualitative aspect, which consists in the preferential allocation of teaching in their own area of expertise. ECRs are encouraged to participate in research training activity, run centrally at University level via RETI as described in the institutional narrative. This is particularly the case for PGR supervision, enabling them to join supervision teams and gain supervision experience. ECRs enrolled on a research career pathway are set probation objectives which give priority to research, and are allowed to complete a mandatory teaching qualification over two years instead of the one year of their probation. A number of University/Faculty funded initiatives specifically target ECRs, e.g. with seedling funding of up to £5,000. Finally, the Faculty organises an ECR Network that provides a forum for peer support, exchange of ideas and interdisciplinary initiatives.

All ECRs have been incorporated into one of the three Research groups: ISEC (2), AI & Data Science (6), CSIG (1). Two ECRs have not been returned to the current exercise, having been appointed after the census date.

b. EDI Strategy

The School promotes Equality, Diversity and Inclusivity (EDI) through the implementation of various support strategies, in accordance with the University guidelines, for academic staff and research students who return from leave, illness, management of long-term illness and/or care responsibilities, as well as for staff with protected characteristics.

Research-related travel (e.g. Conferences, Short Courses, etc.), including for those who are negatively affected (e.g. caring responsibilities, ill health, etc.), is supported by competitive funds made available by the School, Faculty, and Research and Enterprise office.

Staff are actively encouraged to participate in EDI initiatives at all levels both within the university and through external organisations (e.g. British Computer Society, Aurora Program of the University, etc.).

Comparing the current EDI related categories (set out in the below table), for UoA11, two of the four categories (BAME and ECR) outperform the equivalent figures at the School level, the Over 55 UoA11 is on par with the figure at the School level, and the remaining category (gender balance) has been highlighted as one that requires further enhancement, given that the for UoA11, this category is lower than the equivalent figure at the School level.

The breakdown for various categories (Submission – School) is as follows:

	Women	ECR	BAME	Over 55
UoA11	16%	47%	42%	26%
School (Computing Discipline)	30%	27%	25%	29%

There is evidence that current research activities (e.g., Machine Learning, Artificial Intelligence, Cyber Security, etc.) has aided the School's recruitment policy. Furthermore, in areas where the School has been identified as lagging behind (specifically, gender balance), the School has initially addressed this by appointing 2 of the 3 current female staff returned for the UoA in the last two years, It is also actively now seeking to address this further from its ongoing recruitment programme. Additionally, there are three female members of staff who will become active for future REF submissions.

c. Postgraduate Research Students Support and development

All Postgraduate Research (PGR) students must complete a period of induction at the start of their studies, and a research skills programme/portfolio prior to completion. Each student is assigned two or three supervisors. The University has a well-developed procedure for monitoring PhD research programmes, administered by each Faculty Research Degrees Committees

(FRDC) and RETI, and supported within the faculty by the Faculty R&E Support Team (FRES), and the faculty PGR network. PhD students from all research groups are invited to speak about their research in an informal way. In addition, students can bid to the Faculty funding to cover conference attendance and fieldwork expenses. The faculty have also supported internal PGR conferences, socials and the University 3-Minute Dissertation (3MT) event.

Most of the above-mentioned sources of funding have been used to support PhD students in the Unit: iCase doctoral scholarships, H2020 projects (via fractional Research Assistantships), as well as some KTP. For the latter, although the majority of these aim at Impact and technology transfer, research contributions also include outgrowth of three PhDs with direct relevance to the newly established AI & DS Research Group).

In addition, the University manages a number of PhD funding schemes centrally, in particular through the competitive Vice-Chancellor scholarships. Over the reporting period, 5 such scholarships have been awarded to the Unit.

3. Income, infrastructure and facilities

a. Research Income

Research funding for the Unit has been provided primarily by competitive grants at national and European level (H2020), with some participation in joint schemes such as CHIST-ERA. National funding has been obtained mainly from EPSRC, with smaller grants from NCSC and the British Council. Some additional research funding has been provided from KTPs, although the majority of these aim for impact and technology transfer.

ISEC's income strategy prioritises research funding in national and international consortia, especially in H2020 and EPSRC grants. Since 2014, it has attracted in excess of £2.3 million in research income, corresponding to 10 successful awards in the area of cyber security funded by H2020, EPSRC and the British Council. 8 of these were secured since ISEC was founded in 2018.

ISEC's current and most recent projects include:

- Co-ordination of the £2.4M EPSRC project CHAI (UoG £453K, 2020-2023), which introduces cyber hygiene to AI-assisted domestic life
- Co-ordination of the €2.9M H2020 project EUNOMIA (UoG €512K, 2018-21), which tackles disinformation in social media
- Co-ordination of the £60k NCSC project MERIT on cyber security investment
- Participation in the H2020 project ENSURESEC (UOG €489K, 2020-22), which develops cyber-physical security measures for e-commerce
- Participation in the H2020 project CUREX (UOG €270K, 2018-21), which allows a healthcare provider to assess the cybersecurity and privacy risks they are exposed to with mathematically optimal strategies
- Participation in the H2020 project C4IIoT (UoG €250K, 2019-22), which builds a unified cyber security framework for detection and mitigation of malicious behaviour in Industrial IoT
- Participation in the H2020 SECONDO project (UoG €250K, 2019-22) on security investment and cyber insurance decision support through game theory
- Co-ordination of the British Council's SecureHajj project (£42K, 2018-19) addressing decentralised authentication for temporary large-scale IoT deployments
- Participation in the EPSRC COCOON project (UoG £185K, 2016-19) leading the development of user-centric intrusion detection in smart home environments
- Participation in the H2020 TRILLION project (UoG €334K, 2015-18) building a secure crime reporting tool for community policing.

CSIG has been primarily funded through national funding initiatives, mostly supported via the relevant Research Councils. Examples of projects undertaken by the Centre are listed below:

- EP/R512278/1. NPIF EPSRC Doctoral (iCASE) award with Ordnance Survey (2017-2021). Award total: £88,508.00. Zena Wood PI, Mike Worboys CoI.

- EP/R044937/1. EPSRC Digital Economy: Digitally Enhanced Advanced Services (DEAS) Network+ (2018-2021). Award total: £1,116,752. Roger Maull PI (University of Exeter). Zena Wood (University of Greenwich), Robert Johns (University of Nottingham), Tim Baines (Aston University) and Sarah Fletcher (Cranfield University) as CoIs.

- The Uber Disruption. Assessing the Impact of Digitisation on Local Transport (2016). Funded by the Research Council UK's NEMODE (New Economic Models in the Digital Economy) Fund. Award total: £25,751. Zena Wood PI, Glenn Parry (University of West England) CoI.

- Using computational methods to produce a taxonomy of business models of the digital economy (2016). Funded by the Research Council UK's NEMODE (New Economic Models in the Digital Economy) Fund. Award total: £11,819.00. Zena Wood PI, Glenn Parry (University of West England) CoI.

- Boriana Koleva (PI), Richard Mortier, Steve Benford (University of Nottingham), John Stell (University of Leeds), Mike Worboys, Anthony Quinn (Central Saint Martins), Liberating Aestheticodes, Horizon, Digital Economy Research, 2014-2105, £170,000, 2014-15.

b. Equipment, infrastructure and facilities

Our IoT and cyber security research focus on impact in physical space requires extensive experimentation with physical systems. The University has purchased two four-wheel-drive Superdroid rovers, a NAO humanoid robot and Arducopter drones to support two PhD completions in cyber intrusion detection and intrusion identification for robots. A smart office living lab has been set up based on over 80 commercial IoT devices, Nvidia Jetsons, network devices, display systems, data storage and processing servers to support two PhD students' research in IoT activity recognition and indoor positioning resilience. In addition, the University has invested in a 160-core Intel Xeon Openstack cloud testbed to support our research in computational offloading of time-critical IoT and security tasks, used as part of two PhD projects. We have also consolidated installations developed as part of externally-funded projects. Our work in smart home cyber security is conducted on a cyber range previously developed as part of EPSRC COCOON and now utilised by further PhD projects. It includes 15 commercial IoT devices, laptops and specialist SDR HackRF and BladeRF boards for offensive IoT exploitation and experimental evaluation of smart home intrusion detection (accepted in IEEE Trans. on Information Forensics and Security).

The requirements of Data Science and Machine Learning research tend to exceed available computing facilities, reinstating the need for specialist equipment and HPC. The University has invested in long-term HPC central facilities with 48 compute nodes, each with 20 CPU cores (2.4 GHz) and 5 GPU nodes with the addition of 2 NVIDIA Tesla K80 per node. Pending a phase II upgrade of the central HPC facilities, the School has procured specialist equipment to support its Deep Learning work, first in the form of an 8 NVIDIA™ GTX 1080 Ti GPUs, 32 Intel™ Xeon CPUs configuration and, more recently, one NVidia V100-powered DGX-1 workstation benchmarked at 500 TFlops. Such specialist equipment has been used to support Deep Learning research into auto-encoders for sequence processing (to appear at AAAI 2021).

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

a. International Collaborations
The School is involved in significant international collaborations through established relationships between individual researchers at Greenwich and colleagues at partner institutions,

as well as participation in international research projects (EU-funded, bilateral, or national initiatives including an international collaboration element).

Key relationships include:

- **MIT CSAIL (USA).** This is a long-term collaboration between TK and Howard Shrobe's team in MIT that has resulted in novel techniques and tools for the end-to-end protection of cyber physical systems, and 9 publications. The collaboration has now expanded to include the University of Patras in Greece and the AI Chip Design Centre in Japan, jointly organising a special session in IEEE ETFA 2020 and 2021.

- **National Institute of Informatics (Tokyo, Japan).** This collaboration is based on non-admissible search and its application to multi-agent path finding for unmanned aerial vehicles. MC visited the NII regularly during the reporting period, including the summer of 2018 and 2019. This collaboration has resulted in papers at AAMAS 2019, IEEE Transactions on Intelligent Transportation Systems, IEEE Transactions on Vehicular Technology and the Journal of Artificial Intelligence in Education. This collaboration is being extended through the formal appointment of MC as visiting professor in 2021.

- **RMIT University, Melbourne (Australia).** MW has a long-term collaborative project with Prof. Matt Duckham in the School of Mathematical and Geospatial Sciences at RMIT. This has led to joint authorship of four papers on computational aspects of geographic information systems in refereed international research journals. MC has an ongoing collaboration with the School of Computing technologies on AI Planning, which led to papers published at AAMAS 2020 and AAAI 2021.

- **The French Atomic Energy Agency (CEA, France).** TK is collaborating with CEA on the development of a specification language and corresponding run-time verification framework for the protection of e-commerce applications in the context project ENSURESEC.

- **Alpen-Adria University (Austria).** TK is collaborating with AAU on developing program analysis techniques to automatically detect and correct errors and security threats. This has led to joint publications in IEEE Transactions on Software Engineering and Empirical Software Engineering Journal. TK is now also serving on the board of international experts in AAU's project SEEROSE.

- **University of Houston (USA).** This collaboration between Manos Panaousis and Aron Laszka's team (Houston) has resulted into a recent publication in IEEE Transactions of Information Forensics and Security, as well as the ongoing preparation of an EPSRC/NSF research bid.

- **Hainan University (China).** This collaboration in AI and optimisation has been supported locally through two joint projects by the National Nature Science Foundation of China and the Scientific Research Fund of Hainan Provincial Education Department. A number of mutual visits took place during the reporting period: Prof Wencai Du visited University of Greenwich in June 2016; JM was formally invited and visited Hainan University 2017; Dr Xiaoyi Zhou, the Head of the School of Information Science and Technology at Hainan University, visited University of Greenwich from Dec 2019 to Jan 2020. This collaboration has produced a total of 19 papers since 2014.

Finally, staff were involved in the organisation of national and international conferences at Greenwich. The CSIG Group organised and hosted GISRUK 2016 at the University of Greenwich. The event saw 35 papers presented, 13 posters and three keynote speakers. Over 100 delegates came from the UK and Europe. It was also in charge of READIE's first annual research conference hosted by the University in March 2016. READIE is a European digital policy centre, set up by Nesta, as an alliance for research and policy into the digital economy in

Unit-level environment template (REF5b)

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2015. There were over 80 delegates from across Europe coming from both industry and academia.

b. Indicators of Esteem
Staff from UoA11 take an active part in the national and international computer science community, in their respective specialisms. As expected, they participate in journal editorial boards and conference programme committees; are invited to give presentations and keynote talks; participate in the peer reviewing of grants and funding applications nationally and internationally.

Editorships	PC Membership	PC and Track Chair	Keynotes	International Grant Reviewing
7	70	9	10	13

Professor Mike Worboys is Editor-in-chief of the Journal of Spatial Information Science and on the editorial board of the International Journal of Geographical Information Science (Taylor and Francis), and of Spatial Cognition and Computation. He was Program Chair of GIS Research UK (GISRUK), Greenwich, UK; and a member of the following programme committees: International Conference on Geographic Information Science (GIScience) 2016, 2014; AGILE Conference on Geographic Information Science 2015, 2014, and the 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems. He gave the keynote address at GISRUK (GIS Research UK) 2014, and was recognised as a Distinguished Scientist of the Association of Computing Machinery

Professor George Loukas is on the editorial board of Elsevier's Simulation Modelling Practice and Theory and the BCS's The Computer Journal and served on the programme committee of several international conferences, including IEEE MASCOTS, IEEE HPCC, IEEE ISPA. He has been a grants evaluator for EPSRC, ESRC, H2020-MSCA (EU), NWO (Netherlands), SNSF (Switzerland), ISF (Israel), MBIE (New Zealand).

Professor Jixin Ma was an invited keynote speaker at the 3rd International Conference on Computer and Communication Engineering Technology (IEEE CCET 2020), International Conference on Computer Vision and Information Technology (CVIT 2020), the 6th ACM International Conference on Applied Computing and Information Technology (ACIT 2018), the 16th IEEE International Conference on Software Engineering Research, Management and Applications (SERA2018), the 10th International Conference on Computational Intelligence and Software Engineering (CiSE 2018), and the 5th Conference on Artificial Intelligence and Data Mining (AIDM 2016), 28 – 30 Nov 2016. He was Program Chair of the 3rd International Conference on Artificial Intelligence and Pattern Recognition (AIPR 2020), of the 3rd International Conference on Computer and Communication Engineering Technology (IEEE CCET 2020), of International Conference on Computer Vision and Information Technology (CVIT 2020), of the 15th ACIS International Conference on Software Engineering Research, Management and Applications (2015); Deputy Track Chair (Application Stream) of the BCS SIGAI International Conference on Artificial Intelligence, 2019-2014; and a Program Committee member for ICCBR 2019,2020, BCS SGAI 2015-2020, AAAI2019, AI 2015-2019.

Professor Marc Cavazza was Senior Programme Committee member for IJCAI 2020, ECAI 2020, ACM Intelligent User Interfaces (2016-2019); exhibition co-chair at AAAI 2015, track chair at ACM multimedia 2014. He also served on the Programme Committee of ACM Multimedia (2017-2020), AAMAS (2015-2019), ACM Virtual Reality Software and Technology (2017;2015), and 20 other conferences over the reporting period (AIIDE, IVA, CASA, SeGAH, Healthinf…). He is Associate Editor of Virtual Reality (Springer). He was keynote speaker at the BCS SGAI Conference 2019, the Annual Benelux Conference on AI 2016, and the International Conference on Principles and Practice of Multi-Agent Systems (PRIMA) 2015. He received the Best Paper Award at the International Work-Conference on the Interplay Between Natural and Artificial

Computation (IWINAC 2015). He has been a grant evaluator for H2020 (Open FET), ARC (Australia), the SNSF (Switzerland) and the French national research agency ANR (2016-2020), for which he chaired the panel for national professorships in Artificial Intelligence (2019).

Dr Georgia Sakellari is on the editorial board of Elsevier's Simulation Modelling Practice and Theory, and on the programme committee of over 20 conferences, including IEEE MASCOTS and IEEE HPCC. She has reviewed for over 20 journals, including IEEE Transactions on Cognitive Communications and Networking, IEEE Transactions on Cloud Computing, Future Generation Computer Systems and others. She has been an evaluator and project reviewer for FET and H2020 EU projects.

Dr Emmanouil Panaousis is a Senior member of IEEE, a research fellow of the Research Institute for Sociotechnical Cyber Security (RISCS) and a member of the EPSRC Associate Peer Review College. He is on the editorial board of IET Information Security, and has previously served as chair and TPC chair of the Conference on Decision and Game Theory for Security (GameSec), as well as on the programme committee of the European Symposium on Research in Computer Security (ESORICS).