Institution: University of Exeter

Unit of Assessment: Computer Science and Informatics

a. Overview

Our research focuses on three main areas of Artificial Intelligence: Machine Learning, Evolutionary Computation and Optimisation, and Knowledge Representation. We have a strong inter-disciplinary outlook and are committed to applying the results of our research to solving "difficult" problems across science and engineering. Since RAE2008, the group has grown by 67% and research income per FTE has risen by an order of magnitude over the census period.

Computer Science research at Exeter takes place primarily within the multi-disciplinary College of Engineering, Mathematics and Physical Sciences (http://emps.exeter.ac.uk) with one member of the group working in the College of Life and Environmental Sciences. Much of our work is interdisciplinary and we collaborate with scientists working across the breadth of the University of Exeter's "Science Strategy". This strategy (launched in 2005 and discussed in the RAE2008 submission) was a £230 million investment by the University in five cross-disciplinary themes: Climate Change and Sustainable Futures, Exoplanets, Functional Materials, Translational Medicine and Systems Biology. Computer Science, with a strong group working on biological problems and bio-inspired computing, contributes particularly to the Systems Biology theme.

b. Research strategy

Our vision is to provide an environment where world-class research in Computer Science is informed by the latest theoretical developments and is applied to problems of societal importance.

Review of strategy

Our aim outlined in the RAE2008 submission has been to develop a strong group of researchers with a coherent research focus, capable of attracting staff and research income. To achieve this our strategy has been to build links between our focal research areas and to transfer the results of our research to external researchers, nationally and internationally.

We believe we have successfully implemented this strategy. We have a clear focus on artificial intelligence and machine learning, with strong sub-groups focused on evolutionary optimisation and on biological problems. Recent appointments have been made in line with our goal of concentrating research focus and attest to our ability to attract world-leading staff (e.g. Akman, Min, Moraglio, Ying). Grant income from a number of sources (RCUK, TSB, EU and industry) has increased substantially and, based on an average of 8.5 FTEs during this census period, annual income per FTE is 30% higher than during the RAE2008 period. Our research community continues to engage high quality research students. Research strategy is managed through the College Research and Knowledge Transfer Executive Group, of which the Director of Research is a member, and is supported by University and College administrative research and knowledge transfer teams.

Future directions

Our primary goal is to ensure sustainable growth of a coherent group, building on our internationally leading research and continuing our collaborations within the discipline, with other academic disciplines and with commercial and industrial partners. We have been successful in collaborations with mathematicians, engineers and biological scientists among others, and we view continued interdisciplinary and applied work as key to expansion, a theme which is reflected in our new undergraduate programmes.

An immediate area of new growth is **High Performance and Scientific Computing** and we are establishing a new group working on fundamental research and forming collaborations across the college and university. We have recently appointed a new Professor of High Performance Computing (Min), a post that will be supported by at least two further posts in the next two years.

This is a university-wide activity that complements our current research, particularly in "big data," (Ying), optimisation (Everson, Fieldsend, Keedwell, Moraglio) and bioinformatics and systems biology (Akman, Keedwell, Yang), as well as giving new tools for physics, engineering and social sciences. The University anticipates an investment of approximately £3M over the next three years in HPC facilities, both locally and in collaboration with Great Western 4 partners (Bristol, Cardiff and Bath) and the Met Office. This investment will be overseen by the High Performance Computing Governance Group, chaired by Everson and including Min. Furthermore, High Performance and Scientific Computing is essential to the climate change and sustainable futures, systems biology and exosolar planets themes of the University's Science Strategy. We also plan to build on a current collaboration with the Met Office, also situated in Exeter, to explore further possible ways of exploiting our expertise. We thus see ample opportunities for new collaborations across the spectrum of science.

An exciting development is a new "Living Systems Institute". This interdisciplinary research centre, housing 200 scientists in a new £50M building, located between the current locations of Computer Science, Biosciences, Physics, Mathematics and Engineering, will be a focal point for biomedical research, in which we will be closely involved through work in bioinformatics, systems biology, evolutionary optimisation, image analysis and high performance computing.

Research in Computer Science in Exeter is now in a favourable position. We are a small, innovative group of researchers with a coherent research programme, working on timely, real-world problems and collaborating across a range of disciplines. Our strong record of achievement is allowing us to establish growth in a new direction. Our prospects are bright and we are determined to make the most of them.

c. People, including:

i. Staffing strategy and staff development

Relation to research strategy

The appointments of Ying as a lecturer in Machine Learning and Moraglio as a lecturer in Evolutionary Optimisation stems directly from our strategy of consolidating a coherent research group focused on machine learning, evolutionary computing and optimisation, and knowledge representation. We have identified high performance and scientific computing as a direction for strategic growth, which has begun with the appointment of Min to a chair in High Performance Computing and Networks and is supported by new junior posts over the next two years.

Career development support

The University operates a 5-year induction and probationary process for all new academic appointments below Associate Professor, during which appropriate research goals for each appointee are specified. At the end of a successful probationary period (which may be accelerated by early achievement of goals) lecturers are promoted to Senior Lecturer grade. New academics are assigned to a research group leader who can offer guidance and support from the outset. As part of their induction, new academics are encouraged to gain experience of supervising a PhD student within the first two years of appointment. A bursary of typically £4k is provided to each new lecturer to spend on research items. We have been successful in providing PhD studentship funding for all academic appointments since RAE2008, namely Akman, Ying, Moraglio, Min, He (who successfully gained a post at the Open University) and Soyer (recently appointed to a chair at Warwick). New academics are encouraged to apply for appropriate RCUK funding, and they are supported in this by the Director of Research, the Research Administrators and by their research group leader; Akman, He, Keedwell and Ying have been the recipients of EPSRC First Grant awards and have progressed to obtain additional funding; Moraglio is preparing a First Grant proposal. Research group leaders support academics via a research travel fund for research conferences, visits etc.

The principles of the *Concordat to Support the Career Development of Researchers* are embedded in the College's procedures. All staff, including post-doctoral research assistants, are formally appraised annually, with additional appraisal and mentoring meetings throughout the year. Outstanding contributions are recognised through an annual merit award system; several post-doctoral research fellows in Computer Science have received merit awards. We encourage

research fellows to participate in the university's Researcher Development Programme, a suite of over 40 workshops covering aspects of research and career management. Most of our research fellows have attended the university's Learning and Teaching in HE or Postgraduate Certificate of Academic Practice programmes to prepare them for applying for academic jobs involving teaching. Similarly, we encourage research fellows to participate in supervision of research students. The College Director of Postgraduate and Postdoctoral Researchers champions all aspects of infrastructure and career development for research fellows.

The College operates a workload system to balance the demands of teaching, research and administration for all staff, including a reduced lecturing and administrative load for new academics. The University aims to provide staff of all levels with appropriate training, including an academic leadership programme for senior academics. We have been successful in encouraging academics to take up opportunities for study leave to allow them to pursue research projects and visits (e.g., Everson, 2011-2012; Ying, 2012, 2013; Žunić, 2013). In addition, flexibility over scheduling of teaching and use of the workload system provide further periods of dedicated research time.

Equality and Diversity
We and the University are committed to improving the poor balance of male to female staff. The University has recognised the principles of the Athena Swan charter, a national charter addressing gender inequalities in higher education (http://www.athenaswan.org.uk), and having gained a Bronze award in 2011 is working towards a Silver award. All staff are provided with equality and diversity training. Within Computer Science, we are working with the University initiative to review our procedures and management to gain a discipline Athena Swan award and to encourage diversity and equality at all stages of an academic career. We are supporting a female member of teaching staff to establish a strong research profile, which will enable her to transfer to a research and teaching role. We actively support and participate in initiatives, such as the Big Bang Science Fairs (http://www.thebigbangfair.co.uk), which promote diversity.

ii. Research students
PhD intake has increased steadily since the last RAE and we continue to recruit excellent research students from home and overseas. During the REF period 18 PhD and 2 MPhil degrees were awarded in Computer Science. We also jointly supervised 2 PhDs in Engineering and 2 in Biosciences.

The *MSc Applied Artificial Intelligence* has attracted high quality students from home and abroad, providing a route for PhD students to join Computer Science, as well as providing additional training in topics such as pattern recognition, machine learning, optimisation and nature inspired computation for direct entry PhD students.

We provide research students with all necessary facilities and support towards successful completion of their studies, e.g., all research students receive a minimum of £1500 to support their project (for consumables, software purchase, conference attendance, etc) irrespective of their source of funding. All students have individual desk space in one of several open-plan style offices in close proximity to computer science staff.

Research student training is regarded as vitally important for the health and sustainability of the unit. In addition to a college-wide research methodology module, all first year research students must attend at least one specialised technical module. Reading groups in research groups sustain students' technical training outside their own particular projects. Skills training (http://as.exeter.ac.uk/support/development/researchstudents/) provided by the University of Exeter is recognised as one of the best in the country. Exeter uses the Research Councils and the QAA interpretation of Generic Skills to provide training in research management, personal effectiveness, communication skills, networking, team-working and career management. In addition to formalised Generic Skills training, Exeter also implements employability skills training to equip postgraduates with the necessary skills, knowledge and training to enter academic or industrial research careers.

In addition to supervisors, all students are assigned a mentor who provides support and participates in progress monitoring. Students undergo formal monitoring after three months (a short review), at the end of the first year (report, presentation, interview and review of formal training) and at the end of subsequent years (reports), to ensure continued progress and identify any potential obstacles; only those students who are making progress and have clear objectives are permitted to continue. PhD students must give at least one research seminar during the first two years of their degree, and are actively encouraged and funded to participate in relevant international and national research conferences and workshops

Many of our PhD students go on to successful academic and highly skilled careers; for example students who graduated since 2008 are working as scientists in the Met Office and GCHQ, as industry research and development scientists, and four are university lecturers. Five now have postdoctoral research positions.

d. Income, infrastructure and facilities

Research Income

Computer Science has attracted income principally from the EPSRC with additional funding from NERC, BBSRC, the European Community, TSB and the Royal Engineering Society. Other external income includes funding from industrial partners such as AstraZeneca, DSTL, Huawei Technologies, the Met Office, Motorola and NATS. Total research income for the census period amounts to £1,290k. Income and income per FTE has risen significantly over the census period: income each year has increased by a minimum factor of 1.5 and income in the last two years of the census period (£1004k) was three times the total over the first three years (£287k).

The establishment of a new High Performance Computing research group at Exeter opens new avenues of funding for us, both within the HPC group (we already have a European Community FP7 grant starting in the new year) and in collaboration with academics engaged in machine learning. We shall also build on collaborations started under initiatives such as the Open Innovation Platform (e.g., Everson on video processing for lameness detection in dairy cows) and the EPSRC-funded *Exeter Science Exchange, Bridging the Gaps* activities that has led to funding proposals with English, Biosciences, Physics and the University of Exeter Medical School.

Infrastructure and facilities

The University has made significant investment into the infrastructure and staffing at all campuses of the University, with over £380 million invested in campus facilities since 2008. This includes a programme of new buildings and updating and refurbishment of all of the academic buildings, such as the Harrison building, where most of the staff and researchers in Computer Science are situated. This has included the updating of general IT systems at College and University levels, expansion of the library and the provision of new high quality office accommodation.
In addition to small research clusters located in Computer Science, we use the high performance machines Zeus (384 core high-throughput system with a total of 250Tb of usable storage connected via QDR Infiniband) and Zen (SGI Altix ICE 8200, with 1920 cores and Dual DDR 4x Infiniband interconnect). As described above, the University anticipates significant investment in high performance computing over the coming years.

e. Collaboration or contribution to the discipline or research base

Recent high-impact, internationally-leading work illustrating our leading role includes:

- Advances on the description of collective phenomena (by Galton and the subject of keynote addresses at the InterOntology Conference in Tokyo and a workshop on Collectives in Space and Time in Rostock, together with Best Paper awards at FOIS2008 and Spatial Cognition, 2008).
- New results on the description of multi-component shapes (by Žunić, who gave an invited talk on it at the prestigious 2011 Dagstuhl Seminar).
- Advances in modelling of network traffic and quality-of-service (by Min resulting in keynote addresses at HPCC2013, ISPA-2013, iThings-2013, ScalCom-2012, CSE-2012 and WNM-2011).
- Eleven best paper awards (2013: Min at GreenCom; Everson and Fieldsend at GECCO;

Everson at UK Computational Intelligence workshop. 2012: Žunić at ICIEV 2012; Moraglio at GECCO. 2010: Min at TrustCom; Moraglio at EuroGP. 2009: Min at CSE2009. 2008: Galton at FOIS2008 and Spatial Cognition 2008; Min at ICAC2008.)

- Development of machine learning algorithms for learning with kernels and metric learning (by Ying and the subject of the book *Learning with Support Vector Machines*) and for bioinformatics (by Yang and described in the book *Machine Learning Approaches to Bioinformatics*).

Academic collaborations

We are very active in research collaborations at international and national levels. Many of the submitted papers are results of these collaborations and here we highlight the co-authorships and grant awards as evidence of recent collaborations.

Internationally:

- **Žunić** is Research Professor at The Mathematical Institute of the Serbian Academy of Sciences and Arts leading to publications in, e.g., *Computers & Mathematics with Applications*. His widespread network of collaborators includes: Reinhard Klette at the University of Auckland (publications in e.g., *Computer Vision and Image Understanding*); Amiya Nayak and Milos Stojmenovic at Ottawa University (e.g, *Pattern Recognition*); and with Kaoru Hirota at the Tokyo Institute of Technology (e,g., *Pattern Recognition*).
- Spatio-temporal concerns underlie a recent collaboration between **Galton** and Worboys of the University of Maine. EPSRC-funded exchange visits led to the development of an ontology of information (including dynamic spatially distributed information) which was presented at ISCRAM 2011. Galton has also collaborated with Mizoguchi (Osaka) leading to publication in *Applied Ontology*, and with Duckham (Melbourne) with publications in *Pattern Recognition* and *IJGIS*.
- **Ying** works on problems in bioinformatics and metric learning with colleagues at City University, Hong Kong and Zheijang University and the Institute of Automation, Chinese Academy of Sciences, resulting in publications in the *Journal of Machine Learning Research*, *IEEE Transactions on Information Theory*, *BMC Bioinformatics* and others.
- **Yang** works with Ganjana Lertmemongkolchai at *Khon Kaen University (Thailand)*, Gladys Tan from the *Defence Medical & Environmental Research Institute (Singapore)* and Philip Felgner from the *University of California*. Their work on analysing *Burkholderia pseudomallei* diagnostic pattern discovery has led to publications in *PNAS* and *Bioinformatics*.
- **Min** has established long-term and fruitful collaborations with Tshinghua University (China), the Chinese Academy of Sciences, City University, Hong Kong, and the University of Sydney in the area of next-generation internet, leading to publications in *IEEE Trans. Multimedia*, *IEEE Trans. Parallel and Distributed Systems, IEEE Journal on Selected Areas in Communications, ACM Transactions on Embedded Computing Systems*, and *IEEE Network*. He coordinates a European FP7 project on quality of experience improvement in heterogeneous wireless networks, involving collaborators from the UK, the Royal Institute of Technology, Sweden, and Tongi, Southwest Jiaotong, Fudan and Wuhan Universities in China. Min leads a further FP7 project (€361k) on mobile social networks with colleagues at the *Norwegian University of Science and Technology, Norway, the University of Essex*, the *Chinese Academy of Sciences, Tsinghua* and *Shanghai Jiao Tong Universities* and the *University of Electronic Science and Technology* in China.
- **Moraglio**'s work on a geometric theory of evolutionary computation has led to collaborations with colleagues at the *University of Seoul (Korea)* and the *University of Milano-Bicocca (Italy)* and publications *(e.g., GECCO, Evolutionary Computation Journal, PPSN).* He also collaborates extensively with colleagues at the *University of Coimbra (Portugal),* where he is a permanent honorary research fellow and co-investigator, resulting in publications at *GECCO* and *Evolutionary Computation*.

Nationally:

- **Yang** works with Zihua Yang from Queen Mary University on a range of topics in statistical modelling. Their work on Bayesian spectral smoothing has been published in *Journal of Raman Spectroscopy* and new methods of detecting outliers in cancer microarray gene expression data will be published in *BMC Bioinformatics*.

- **Akman** works with Andrew Millar FRS (SynthSys, Edinburgh) and Stuart Aitken (MRC, Edinburgh) on models of circadian systems, with a particular emphasis on robust techniques for statistical parameter inference in high-dimensional models. This BBSRC-funded work has led to publications in *BMC Systems Biology* and *Bioinformatics*. Akman also works with David Broomhead and Richard Abadi (Manchester) on combining neural population modelling with time series analysis to characterise the development of neurological tremor disorders (*Brain Exp. Res.).* He also has a long-standing, EPSRC-funded collaboration with Orkun Soyer and Declan Bates (Warwick) on using *in silico* evolution and control theory to understand how robustness can be engineered into both natural and synthetic biochemical networks.
- **Žunić** and Paul Rosin (Cardiff University) have a fruitful collaboration on aspects of shape analysis. Recent work on multi-component shapes was the subject of an invited talk at the 2011 Dagstuhl Seminar and at the Institute of Automation, Chinese Academy of Sciences. He also works with Martin Huxley (Cardiff) on digital geometry and number theory resulting in publications in *Proc. London Mathematical Society* and *Forum Mathematica*.
- **Galton**'s work on discrete mereotopology has led to a recent collaboration with Gabriel Landini and David Randell from the Birmingham School of Dentistry in developing the use of novel methods for interpreting histological images and a joint publication in *IEEE Transactions on Pattern Analysis and Machine Intelligence.*
- **Ying** and Campbell (Bristol) have written a series of highly cited articles on kernel methods and they have jointly published a new book *Learning with Support Vector Machines*. Ying also works on multi-task learning and multiple kernel learning with Pontil and Girolami at UCL, resulting in publications in *NIPS* and the *Journal of Machine Learning Research*.
- **Min** works with Ahmed Al-Dubai (Edinburgh Napier University), Jianmin Jiang (University of Surrey), and Qiang Ni (Lancaster University) on wireless multimedia networks. They have generated new analytical models and protocols for Next-Generation Internet and publications in *IEEE Transactions on Communications* and *IEEE Transactions on Wireless Communications*.

Within Exeter University:

- **Yang** works with Exeter biologists, Murray Grant and Nick Smirnoff for metabolite pattern analysis resulting in publications in *PloSOne* and *Metabolomics*. He also collaborates with Exeter physicists Peter Winlove and Julian Moger on modelling Raman spectra resulting in publications in the *Journal of Spectroscopy*.
- **Keedwell's** EPSRC-funded work with the University of Exeter Medical School is focused on using nature-inspired algorithms to mine disease associations (such as Type-2 Diabetes) from genome-wide association study data and is published in, for example, *Information Sciences*.
- Work by **Keedwell** on evolutionary algorithms has been important for the internationally-renowned Centre for Water Systems' optimisation of water distribution networks (see Impact Case Study). His paper on hybrid genetic algorithms was the top-cited paper in Engineering Applications of Artificial Intelligence between 2005 and 2010. With the Centre for Water Systems he has developed cellular automata for modelling flood risk and was recently funded by EPSRC to investigate the application of these models on graphical processing units.
- Work by **Everson** and the Biophysics group on point set matching has led to publication in *Biomaterials*. Work with Bioscientists on citizen science for the annotation of microscopy images received the Best Student Paper prize at the *UK Computational Intelligence workshop* (2013). His research in statistical pattern recognition has been key to a NERC-sponsored project with Tom Tregenza in the Centre for the Ecology and the Environment to track whole populations of crickets through large scale video monitoring.
- A number of fruitful collaborations are carried out through joint-supervision of PhD students. For example, **Everson** works with biophysicists on 3D image segmentation, with bioscientists on artificially intelligent foraging, with colleagues in Engineering on the efficiency of additive layer manufacturing systems (TSB) and on the use of web-based tools for co-creation using additive layer manufacturing (EPSRC), with publications in the *Intl. Journal of Advanced Manufacturing Technology* and *Journal of Materials Processing Technology*. **Akman** and **Keedwell** supervise students with mathematicians and bioscientists in the Systems Biology Science Strategy Theme and **Keedwell** supervises Engineering students in the Centre for Water Systems.

Collaborations with industry and research users

As a group we are committed to applying the fruits of our theoretical researches to real-world problems. Industrial and user collaboration is an important part of our research culture and we have developed a fund of expertise that has resulted in fruitful collaborations with a range of organisations, internationally and nationally, who are keen to exploit the technological possibilities in the drive to make machines more `intelligent'. These collaborations, through industrial partnerships on RCUK projects, CASE awards, KTPs, contract research and consultancy, are described more fully in the REF3 documents. Here we briefly mention funded exemplar collaborations: NATS, Motorola, AI Corporation, IMC Ltd., Met Office (Everson and Fieldsend); AstraZenica, DSTL, (Yang); Huawei Technologies European Research Centre (Min); Mouchel Ltd., (Keedwell); Royal Devon and Exeter Hospital (Ying, Keedwell, Everson).

Leadership and contribution to the discipline

Staff in Computer Science are very active in organising and contributing to scientific committees of research meetings and workshops, including, for example, **Everson** and **Keedwell** were co-chairs and **Fieldsend** and **Galton** were members of the organising committee of the annual convention of the **Society for the Study of Artificial Intelligence and Simulation of Behaviour** (AISB) which we hosted in Exeter in 2013. **Keedwell** organised the **Nature Inspired Computation and Applications** symposia at AISB 2012 and 2013**. Akman** and Soyer held the **Frontiers of Multidisciplinary Research**, a week-long international systems biology conference in Exeter (2010), together with an international one-day hot-topic workshop on Oscillation Dynamics in Neural and Biochemical Systems. **Galton** was Programme Chair for **FOIS2010**, General Chair of the **Workshop on Identifying Processes and Events in Spatio-Temporally Distributed Data** (IOPE 2011) held at COSIT 2011, and co-chair of **COSIT 2013**. **Galton** organised a symposium on **Understanding and Modelling Collective Phenomena** at the **AISB** convention in 2012. At the 2012 and 2013 Genetic and Evolutionary Computation Conference **Keedwell** organised workshops on **Problem Understanding and Real World Visualisation**, and **Everson** and **Fieldsend** organised the workshops on **Visualisation in Genetic and Evolutionary Computation**. **Moraglio** was conference chair of the **EuroGP** conference in 2012 and 2013, and the publication chair in 2009. He was workshops chair of the **Parallel Problem Solving from Nature Conference** in 2012, and he is member of the steering committee of **Evo***, which combines five conferences on bio-inspired computation**. Min**'s conference leadership has been recognised by two IEEE Outstanding Leadership Awards for chairing the IEEE conferences **TrustCom'2012** and **CIT-2010**, **ScalCom-2010** and **ICESS-2010**, together with Outstanding Leadership Awards for co-chairing the **ScalCom'2009** and **HPCC'2008** conferences, and an Outstanding Service award for co-chairing the IEEE/ACM **IUCC'2011** conference. As the growth of the group brings new opportunities for contributing to the discipline and enriching the environment in Exeter, we plan a programme of hosting national and international meetings in Exeter; already confirmed is the **UK Computational Intelligence** workshop in 2015.

We contribute to the life of the discipline via journal editorships and memberships of editorial boards including the following: *Applied Ontology* (Galton), *Artificial Intelligence Journal* (Galton, Associate Editor), *BMC Bioinformatics* (Yang, Associate Editor), *Chinese Journal of Biology* (Ying), *ICST transactions on Distributed Multimedia* (Min, Area Editor), IEEE Transactions on Cybernetics (Yang, until 2009), *International Journal of Parallel, Emergent and Distributed Systems* (Žunić), *ISRN Artificial Intelligence* (Keedwell), *Journal of Earth Science Informatics* (Galton, Associate Editor), *Journal of Information Technology and Applications* (Min), *Journal of Spatial Information Science* (Galton), *KSII Transactions on Internet and Information Systems* (Min), *Pattern Recognition* (Žunić, Associate Editor), *Spatial Cognition and Computation* (Galton). Min serves on the editorial boards of 10 journals. We have been guest editors for a wide range of special issues.

Fieldsend sits on the British Computer Society, South West Branch committee.

Everson, Galton, Keedwell and Min are members of the EPSRC review college. Žunić is a programme evaluator for the Romanian Partnership Programme for Joint Applied Research Projects. Min is an evaluator for Netherlands Organisation for Scientific Research (NWO), the UK-India Education and Research Initiative, and the Royal Society.