Institution: University of Birmingham

Unit of Assessment: UoA 11 – Computer Science and Informatics

a. Overview

Computer Science at Birmingham is a research intensive school of international standing. Its research is organised into seven research groups, with some overlapping group memberships.

1. *Artificial Intelligence and Intelligent Robotics Group (**AIIR**)*.
2. *Natural Computation Group **(NC)**.*
3. *Medical Imaging and Image Interpretation Group (**MIII**)*.
4. *Human Computer Interaction Group (**HCI**)*.
5. *Security and Privacy Group (**SP**)*.
6. *Software Engineering Group (**SE**)*.
7. *Theory of Computation Group (**Theory**)*.

The boundaries among research groups are not rigid. Research activities are equally focused within a research group and beyond. Inter- and multi-disciplinary research is a strong feature of our research ethos. This document will use the group abbreviations, as above, for brevity.

The School has grown substantially since last RAE by recruiting 14 outstanding staff members, while seven retired or left for other places. The staff growth is part of University's multi-million pound strategic investments in major initiatives, in which Computer Science play a leading/major role (Para. 4 in Section b). Our annual grant capture has doubled in the last year, with £6.20m new grants in 2012-13 alone (Para. 1 in Section d). The School was ranked the 1st in the 2014 Guardian University Guide and the 4th in the 2013 Sunday Times League Table. Our research excellence has been recognised by prestigious awards, including a Royal Society Wolfson Research Merit Award and outstanding papers awards from *IEEE Transactions* and other international journals (Paras. 4-6 in Section e). Our students won three national and international outstanding PhD dissertation awards in the REF period (last Para. in Section c).

b. Research strategy

Computer science at Birmingham focuses on long-term, fundamental research challenges of relevance to the discipline and society in general. **Our vision** has always been to deliver world class research outputs with long-lasting impact by appointing outstanding researchers, including both established research leaders and early career researchers, in a supportive, collaborative and stimulating environment.

The strategic vision outlined in RAE2008 was to **"deepen excellence in core CS areas whilst further developing our strengths in selected interdisciplinary and application areas"**, which has been pursued and implemented during this REF period. **Our staffing strategy** reflects our overall research strategy of pursuing excellence. Since 2008, we have appointed 14 world-class research leaders and outstanding early career researchers in both core CS and interdisciplinary areas. Three existing staff members were promoted to Professor. The number of Category A staff has increased from 34.0 in 2008 to 39.6 in 2013.

We have pursued our strategy of deepening excellence by increasing our research outputs (in terms of volume) and their international impact, evidenced by outstanding paper awards, research achievement awards and international competition awards. (See Pars. 4-6 in Section e.) We have further enriched our research environments, e.g., through the sabbatical scheme and a unique £1m endowment from Paul Ramsay, an alumnus and PhD graduate, and grown the vibrancy of our research community.

To further develop "our strengths in selected interdisciplinary and application areas", we have led large-scale inter-disciplinary research initiatives within the University and beyond, e.g., the *Centre for Computational Neuroscience and Cognitive Robotics (CNCR)* with Psychology, the *Human-Computer Interaction Centre (HCI)* with EECE (Electrical, Electronic and Computer Engineering), *Doctoral Training Centre PSIBS: Physical Sciences of Imaging in the Biomedical*

Sciences (with Biosciences, Chemistry, Engineering, Medicine and Physics) (Life Science Interface: EPSRC. MRC, BBSRC), the *EPSRC-GCHQ Academic Centre of Excellence in Cyber Security Research* (ACE-CSR), the *USTC-Birmingham Joint Research Centre in Intelligent Computation and Its Applications (UBRI)* with the University of Science and Technology of China (USTC). We are also an active partner, with a new lectureship appointment, in the university-wide initiative in *System Science for Health (SSfH)*.

The AIIR group, especially in intelligent robotics, has grown substantially, as part of a £1.74m university strategic investment in a new *Centre for Computational Neuroscience and Cogntiive Robotics (CNCR)* led by Prof. Wyatt from CS in collaboration with Psychology. One professor (Leonardis), two lecturers (Hawes and Mistry), and a robotics designer were appointed in robotics, plus Bohnet in Natural Language Processing (NLP). Furthermore, Wyatt was promoted to Professor, Dearden to Reader and Hawes to Senior Lecturer. **In line with our deepening excellence strategy**, we published in top journals such as IEEE T-PAMI and AIJ and top conferences such as IJCAI and AAAI, and secured £8.3m in external research funding since 2008. Wyatt and Dearden won a *2008 ICAPS Distinguished Paper Award*, and a further *best paper award at BCS-SIGAI 2008*. To create a flow of trained researchers and ensure research sustainability, an MRes in Computational Neuroscience and Cognitive Robotics and a research driven MSc in Robotics have been set up. As another example of **implementing our strategy in pursuing high-quality inter-disciplinary research**, Kerber teamed up with an economist (Colin Rowat) to apply, for the first time, methods and tools from mathematical knowledge management and theorem proving to theoretical economics (funded by EPSRC). Our NLP researchers (Barnden, Bohnet and Lee) have developed new collaborations with psychologists, in addition to linguists. They secured Leverhulme funding for ground-breaking interdisciplinary work between AI, linguistics and philosophy and Marie Curie funding for applications to intelligent healthcare technology. Building and promoting open tools is an important part of our research and impact strategies: Bohnet's open source parsing technologies (in https://code.google.com/p/mate-tools/) are used worldwide (~960 downloads), as is the CAST cognitive robot architecture (SourceForge, 2000+ downloads). Bohnet's tools are being developed further under a Marie Curie Career Integration Grant and a new FP7 grant (iPatDoc, on patent processing) for research for the benefit of SMEs. As an example of **relevance of our research to society at large**, Sorge and Sexton's work in document (including mathematical and chemical) recognition has not only won an international competition (Image-to-Structure Task at Trec 2011), but also been adopted by Google in its latest ChromeVox version for better web accessibility, especially for visually challenged people. Sorge and Sexton have also collaborated with Lee (NLP) on research contributing to the centralised European Maths Library (EuDML), working closely with mathematicians and publishers (Springer, Zentralblatt MATH).

The research within the NC group covers both theories and applications of nature-inspired computation, especially evolutionary and neural computation. In the NC group, Rowe was promoted to Professor and Tino to Reader. We appointed a new lecturer as part of University's *Systems Science of Health (SSfH) initiative*, He, and a Birmingham Fellow, Zarges. Until his appointment in 2009, He was a Leverhulme Early Career Fellow in our School. The Birmingham Fellowship is a permanent academic post and has five years with protected time for high-quality research. It is awarded to only "the brightest and the best from around the world" in their early careers. The research from the group members continue to lead the world in their topic areas, **following our strategy of deepening excellence**. Yao and Tino won the *2010 IEEE Transactions on Evolutionary Computation Outstanding Paper Award* and the *2011 IEEE Transactions on Neural Networks Outstanding Paper Award*. Yao also won the *2010 BT Gordon Radley Award for Best Author of Innovation (Finalist)*. Rowe won the *2011 International Journal of Intelligent Computing and Cybernetics Best Paper Award*. He won the *ICI Prize for the Best Paper Published in Transactions of the Institute of Measurement and Control in 2012*, which will be presented at Institute's 2013 Presidential Lecture and Learned Awards Evening in London. Zarges won the *ICARIS'2011 Best Paper Award*. Kaban won *the GECCO'2013 Best Paper Award in the EDA track*. Two of our PhD graduates won the *2009 and 2011 IEEE Computational Intelligence Society Outstanding PhD Dissertation Awards*, respectively. We are the only group in the world that have produced two winners. One PhD graduate won the *2009 BCS Distinguished Dissertations Runner-*

up Award. Three other PhD graduates won *two Leverhulme Early Career Fellowships* and *one EPSRC Theoretical Computer Science Postdoctoral Fellowship*, respectively. As a contribution to the sustainability of the UK CS community, five of the group's research fellows secured permanent lectureships or independent fellowships at Universities of Nottingham, Sheffield (2), Exeter, and Aston. A sixth one won a full professorship at a top Chinese university through the Chinese government's *One Thousand Talent Programme for Young Researchers*.

The MIII group appointed a senior lecturer (Dehghani) following a successful bid for £7.1m to the ESPRC to deliver the **Physical Sciences of Imaging in the Biomedical Sciences (PSIBS) DTC, a result of our strategy of "further developing our strengths in selected interdisciplinary and application areas". The group played a leading role in the multi-disciplinary bid and have had crucial roles in the successful management of the PSIBS DTC.** Claridge's research generated substantial impact in industry (see our impact case studies) in addition to academic papers. During the REF period, the group has held funding from EPSRC, NIH, charities, and was part of a successful CIF bid. Significant internal investment from CS's Ramsay funds enabled the refurbishment of dedicated space to provide a substantial and well-equipped research laboratory for the group. The group collaborates widely both within the University across the range of biomedical sciences, and externally with national and international collaborators. Dehghani's software package, NIRFAST, has been downloaded ~2000 times. Students supervised by Dehghani and Styles won prizes at the *2012 OSA Biomedical Topical Meeting* and the *2013 European Conference on Biomedical Optics*. Styles also won funding from the National Physical Laboratory to support his PhD students.

The HCI group expanded considerably in the REF period following a strategic investment from the University. Beale was promoted to Professor, and proposed and led the creation of an interdisciplinary *Human-Computer Interaction Centre*, to maximize the synergy in existing activities especially between CS and EECE. This led to the appointment of two new professors, one full-time (Howes) and one part-time (Dix), and one senior lecturer (Musolesi). The Centre has 9.2 FTE PhD students and 8 FTE Research Fellows. The Centre started a new MSc in HCI. Its income since inception has been over £21m, shared between CS and other schools within the University. The research excellence of this group is underpinned by both basic research and applied work. Not only do group members publish in top venues, such as ACM CHI, UbiComp and MobiCom, and IEEE Transactions on Mobile Computing, but they have also won high-profile international competitions (by Musolesi and his team), including *the Nokia Mobile Data Challenge 2012* (co-located with Pervasive 2012 in Newcastle) and *the Data for Development Challenge in May 2012* organized by Orange and MIT Media Lab (co-located with NetMob 2013 in Cambridge, MA, USA).

The SP group appointed three outstanding young researchers, two as lecturers (Cova and Nagaraja) and one as a Birmingham Fellow (Garcia). The group hosts an EPSRC Leadership Fellow (Ryan) and became *an Academic Centre of Excellence in Cyber Security Research (ACE-CSR)* through a competitive EPSRC bid. The group's work has produced substantial impact internationally, from Ryan's work on TPM protocols, Chothia's work on e-passports, Cova's work on malicious web attacks, to Garcia's discovery of flaws in car security systems and the London Oyster card system. All such work has been underpinned by sound science, published in top journals and conferences, and generated significant impact on industry as well as society (see the case studies).

The SE group is establishing itself quickly on the international stage and is active in leading architecture, modelling, cloud and search-based SE conferences, e.g. WICSA, Models, Services, and SSBSE. A new lecturer (Parker) was appointed. Bahsoon and Bordbar were promoted to Senior Lecturers. All group members published in top SE journals, such as IEEE TSE or ACM TOSEM, **reflecting our core strategy of deepening excellence**. The group has 15 PhD students (July 2013), covering a range of SE topics, including model-based SE, software verification, software architecture, and search-based SE. Its research has generated significant impact internationally, including both publications and open-source tools, e.g., Parker's probabilistic verification tool, PRISM (34,000+ downloads so far), and Bordbar's automated UML model analysis tool, UML2Alloy (2,400+ downloads). Bahsoon's recent work on SE in/for the Cloud and software architecture has led him to guest co-editing journal special issues and book volumes with leading SE researchers from USC, CMU, Lero, Tufts, UCL, Infosys, IBM and Siemens. Parker was

among the first in the world applying probabilistic model checking to biological systems. In search-based SE, the SEBASE project (a £2.6m joint EPSRC project between UCL, York and Birmingham; Yao and Bahsoon) was shortlisted in 2012 by The Times Higher Education Awards for the award of *"Research Project of the Year"*. We are currently a partner of the on-going £6.8m EPSRC Programme Grant on "**DAASE: Dynamic Adaptive Automated Software Engineering".**

The Theory group made three outstanding appointments, one lecturer (Parker) shared with the SE group, one Birmingham Fellow (Krishnaswami) and one Marie Curie Intra-European Fellow (Rivieccio). Ghica and Levy were promoted to Senior Lecturer. The group hosted two EPSRC Advanced Fellows (Ghica and Levy) and regularly hosts seminars by distinguished external speakers, such as Moshe Vardi from Rice and Gerard Berry from INRIA. The group is highly active in the leading theoretical conferences (LICS, POPL, MFPS, etc.) and journals (TCS, MSCS, LMCS, etc). Members have given keynote lectures and tutorials on numerous occasions. Jung, in collaboration with Rowe, for the first time applied tools in the domain theory to analyse co-evolutionary algorithms. Ghica started a collaboration with hardware designers through two very successful interdisciplinary workshops. The first one led to the part-time professorial appointment of Satnam Singh (formerly Microsoft, now Google). The second one, sponsored by EPSRC, was the opening event of its MACDES initiative. The group is also a major player in the national "Computing at School" initiative and the Midland Graduate School in the Foundations of Computer Science in order to enhance the sustainability UK CS from the grassroot level.

Since RAE2008, one staff member has retired and six have left for other universities or industry.

Looking forward, our focus on delivering world class research outputs with long-lasting impact remains unchanged. **We will continue to deepen our excellence in core CS areas and selected interdisciplinary and application areas, as exemplified above by the existing seven groups, and to attract talents at all levels, from research leaders to research students, to join our vibrant community of scholars. Our priority for hiring new staff members will follow this strategy and emphasize highest quality in research.** Given this pre-requisite in quality, our future hiring areas will be influenced by grand challenges to our society, including data deluge, security, and health. Our staffing strategy does not rely entirely on University investments. We will actively attract and nurture research talents to apply for various independent fellowships hosted by us, including research professorships/fellowships from RS, RAEng, Leverhulme, UK Research Councils, Wellcome Trust, and EU. While we are fully committed to provide the best possible environment and support to everyone to develop and pursue their own research agenda, we also encourage more and closer collaborations among research groups in order to take on larger and longer-term research challenges. We want to build up critical mass in areas that we have expertise and are internationally leading. We want to create and strengthen overlaps among research groups so that we can tackle larger challenges that individual groups found hard to do by themselves. **We want to create and strengthen intersections between computer science and other disciplines so that we can contribute to tackling grand challenges in the society, whether they are related to data deluge, security, energy, environment, or health.**

To further enhance the vibrancy of our research environment, we will continue to maintain a very large number of active research seminars. In addition to the School seminar series, we have specialist seminar series in Artificial Intelligence and Natural Computation, Theory, Security, HCI, Topology, and Imaging and Visualisation. We also have informal seminar series, such as Student Cake Talks and Theory Lab Lunches. This unusually large number of seminars are providing a stimulating research environment for our researchers and for collaborations with researchers from outside the School

c. People, including:

i. Staffing strategy and staff development

Our staffing strategy is aligned directly with our research strengths and vision for future development. Our aim has always been to deliver world-class research outputs of long-lasting impact in all our research areas. Our most important criterion in recruitment is always the quality of the candidate and his/her research, not his/her particular research areas or topics.

However, this does not mean we do not have preferences. Our preferences are guided by our strategic vision and research strategies (See the previous section). **Such strategic thinking has led us to make appointments** in the areas of Intelligent Robotics (Leonardis, Hawes and Mistry) to capitalise the collaboration between CS and Psychology; HCI (Howes and Musolesi) to strengthen the shared expertise between CS and EECE; Computer Security (Cova, Nagaraja) to push forward the university-wide research theme on security (not just *computer* security); Medical Imaging (Dehghani) to lead and strengthen links with biomedical researchers across the university and clinicians at the Queen Elizabeth Medical Centre; Computational Biology (He) to strengthen the collaborations among CS, Biosciences and Mathematics; Software Model Checking (Parker) to link and contribute to at least three research groups in SE, Theory and SP; and Natural Language Processing (Bohnet). In addition, we have made use of the University's "Birmingham Fellows" scheme to appoint three outstanding members of staff in Theory (Krishnaswami), Natural Computation (Zarges) and Security and Privacy (Garcia). Of 14 new members of staff, eleven are international appointments. **Of 43 (head count) submitted staff members, 26 are international (non-UK).** Additionally, we have created part-time positions for three people: Satnam Singh (Research Prof., Microsoft and now Google); Alan Dix (Research Prof.); Jeremy Baxter (Research Fellow, Qinetiq).

To support the growth in research (partially driven by new recruits), we have remodelled our physical environment to create more dedicated research laboratory facilities in Intelligent Robotics, HCI, Computer Security and Medical Imaging, in addition to new academic office space and visitors' office. **We hosted 60+ research visitors from 19 countries in the REF period.**

The School has a well established mentoring scheme **for new staff members, especially early career researchers**. Every new lecturer (and Birmingham Fellow) is assigned a mentor, who is a senior staff member in the School and trained by the University for this role. The teaching and admin loads of the new lecturers are reduced by 50% during their probation period, typically three years. In the allocation of Research Committee's resources, e.g., travel funding and Ramsay Research Funds, new staff members always have higher priority. They also have higher priority in winning school's PhD student funding. Probationers take the Postgraduate Certificate in Academic Practice which, in addition to training in Teaching and Learning, offers modules in Designing Research and Effective Research Leadership.

In addition to mentoring new lecturers, research fellows are also being mentored by their principal investigators, e.g., being recommended to serve in the international conference committees and journal editorial boards, nominated for international awards, recommended to be invited speakers at international conferences, and **supported in career development** in general. All these are essential in developing the next generation of UK researchers to lead the world in their fields. For example, the NC group alone had five research fellows secure their lectureships in UK universities.

Academics who have passed the probation period have an annual performance development review process with the Head of School. Training can be offered where needed. For more established academics, the University's "People and Organisational Development" unit (POD) offers training in such subjects as Project Management; Mentoring; Research Team Leadership. For senior academic POD organizes the Senior Leadership Programme, for those developing a leadership or management role.

For all existing staff members, there are annual reviews carried out by either the Head of School or another senior staff member. There is also a long-established and well-managed sabbatical scheme within the School. All applications for sabbaticals, which include a mini-research proposal, are first evaluated by the School Research Committee, before they are passed to the School Staffing Committee for final decision. Sabbatical leavers are encouraged to study away from Birmingham in order to better focus on their research. In the REF period, 23 staff members took their sabbaticals, representing more than 2/3 of all eligible staff members in the school. In short, the School provides an extremely supportive and stimulating environment for staff members at all academic stages.

The School has **a strong commitment to equality and diversity**. It formed a Diversity Group that is chaired by the Deputy Head of School and has representatives from all staff and student levels. The group meets monthly and is leading the school's efforts to address diversity issues locally and

in the sector. The School supports and implements policies for maternity, paternity and adoption leaves not only for teaching staff but also for all research staff. The School is submitting an application for the Athena SWAN Bronze Award in November 2013. While the school has a long history of engaging with equality and diversity initiatives, for example by hosting the 2011 Ada Lovelace colloquium, it has taken on a more active agenda as a result of the Athena SWAN initiative. An ongoing objective is to monitor local equality and diversity data. Our initial study of these data has uncovered that one overwhelming issue is a pipeline problem. Too few women choose to start a computer science career. With this fact in mind we have sought to raise awareness of computing in schools. We have secured Birmingham Alumni Impact funding for a project that seeks to engage girls in computer science education with outreach workshops. This project will be rolled out in 2013/14. In addition, we play a key role in the "Computing at School" initiative which holds its annual conference at the University since 2009. We are also seeking to ensure that our internal processes and culture are conducive to creating an environment in which female computer scientists can prosper and reach senior positions. For example, we are demanding that gender diversity issues are explicitly considered at all appointment and promotion panels. In addition, support for flexible working is a key objective. As part of the University, we were awarded the HR Excellence in Research accreditation in September 2011 and continue to work towards full implementation of its Concordat action plan by September 2013.

Six members of staff held or are holding Fellowships in the REF period: Ryan (EPSRC Leadership Fellow 2010-15), Levy (EPSRC Advanced Fellowship 2008-12), Ghica (EPSRC Advanced Fellowship 2006-11), Wyatt (Leverhulme Research Fellow 2006-08), He (Leverhulme Early Career Fellowship 2007-09), and Riveccio (Marie Curie Intra-European Fellowship). One EPSRC Theoretical Computer Science Postdoctoral Fellow (Oliveto, 2010-13) took up a Vice-Chancellor's Fellowship and then a lectureship at Sheffield in October 2013.

ii. Research students

PGR students are recruited from around the world. On 31/7/2013 we had 86 active PhD students, including 59 normally registered and 27 thesis awaited (writing-up), while on 31/7/2007 we had 64 active PhD students (34.4% increase over the last RAE), including 45 normally registered and 19 thesis awaited. Often, applicants will discuss research possibilities with potential supervisors informally. Formal applications then pass through several stages, from checks on qualifications, through a review by four or five academic members of staff, to interview by two academics. In case of technically difficult subject areas (such as theory) an informal test is also used to evaluate applicants' capabilities.

All new PGR students undergo training as part of **our career development support** to them. Within the School, they attend a taught module on "Research Skills" which covers generic Computer Science research skills. Additional area-specific training is given as necessary. For example, the School participates in an annual Midlands Graduate School which provides training in theoretical topics. More generic training is provided by the University's Graduate School which has a wide range of courses related to research and personal development. PGR students involved in teaching receive training within the School (providing subject specific guidance, for example in running lab sessions) and with the University's Centre for Learning and Academic Development (CLAD).

All PGR students are fully integrated into School's research activities. Not only do they participate in various school research seminars, they also organise their own weekly "Cake Talks", where they present and discuss research ideas informally. They organised one successful Computer Science Day where they invited PGR students from outside CS to pose challenges to computer scientists. The School has always allocated funding to support such activities.

PGR student progress is monitored via a "thesis group". For each student, this comprises the supervisor, a member of the School's Research Student Monitoring Group (RSMG), and a third member (usually a subject specialist). Students write progress reports every six months which are then presented and discussed at meetings of the thesis group. Recommendations concerning progress and any required remedial action are then discussed by RSMG and implemented by the Research Student Tutor. This is an established role within the School. The Tutor has oversight of

all PGR students, and chairs RSMG.

The achievements of our PhD students have been outstanding, evidenced by their winning international and national awards: the *2011 IEEE Computational Intelligence Society Outstanding PhD Dissertation Award* (Huanhuan Chen), 2009 *CPHC/BCS Distinguished PhD Dissertation Runner-up Award* (Huanhuan Chen), *2009 IEEE Computational Intelligence Society Outstanding PhD Dissertation Award (*Siang Yew Chong), and many outstanding paper awards from journals and conferences. These awards represent additional evidence for our successful strategy of deepening excellence. They also indicate the vitality and sustainability of our research.

d. Income, infrastructure and facilities

From 1/8/2008 to 31/7/2013, we have secured a total of £16m external funding, in comparison with £12.6m secured in the last RAE period, which represents a 27% increase. (Note these figures are grants awarded, not actual spending, in the relevant periods.) The two major sources were OST Research Councils (£7.3m) and Government bodies in the EU (£6.7m). Our upward trend can be seen from last three years' grant capture: £2.29m in 2010-11, £2.72m in 2011-12, and £6.20m in 2012-13. In the REF period, 29 of our staff members have had external grants held in Birmingham. The **total amount and the spread** of grant awardees clearly demonstrate **the sustainability of our research**. In terms of grant expenditure, there is a similar growth:

	08/09	09/10	10/11	11/12	12/13
REF4b	*£1,707,155.00*	*£1,916,275.00*	*£2,355,855.00*	*£2,598,120.00*	*£2,787,075.00*

Our research and staffing strategies of deepening excellence and emphasizing larger and longer-term research challenges lead naturally to our future plans for research funding: we will continue to enhance our effort in securing longer-term research grants to support our ambition in tackling major research challenges. The two major sources in this endeavor will be OST Research Councils and Government bodies in the EU. In particular, we will substantially strengthen our effort in nurturing applicants and developing proposals for independent research fellowships from EPSRC, Royal Society, Royal Academy of Engineering, Leverhulme, other UK research councils, and foreign governments and foundations. Two other important sources of funding for us come from industry and overseas. We have a dedicated Business Development Manager and an International Engagement Officer working with us, to exploit our internationally leading research for the benefit of UK industry and attracting more research funding from overseas to Birmingham (for which we had £644K in the REF period).

We have nationally leading robotics facilities (116m2 of purpose built lab space) for both mobile and manipulation robotics. We have three different human height mobile platforms, each with laser, bumper, and sonar sensors, wide and narrow angle cameras, and pan-tilt stereo heads, operating over a dedicated wireless network. We have a tracked platform with a pan-tilt unit with laser range finding, and visible light, zoomable and infra-red cameras; and ten P3-DX robots with cameras, laptops, sonar, and laser for multi-robot research. For manipulation we possess a lightweight arm for mobile manipulation, a Kuka industrial arm, a DLR-HIT2 five finger robot hand, and a suite of F/T and matrix sensors for contact sensing. We have developed a bi-manual half-humanoid torso for advanced manipulation comprising a KIT 7DoF stereo head with four cameras, a bespoke torso, two Kuka LWR4+ lightweight actively compliant 7DoF arms, a humanoid hand from the University of Pisa. We have also developed and maintain our own software toolkit for advanced manipulation (GOLEM), and have access to the surface mount electronics, design and machining facilities at the Manufacturing Technology Centre of which UoB is a research partner. We have hired our own robotics engineer and established a workshop. We have our own GPU compute server for high performance computing. The value of our lab equipment exceeds £0.5m; funded by FP7, Advantage West Midlands (the former regional development agency), and the University.

Our HCI lab hosts a Microsoft Pixel Sense device, which is a large touch enabled display configured horizontally like a table. It enables us to develop interfaces that are touch enabled (like a modern smart phone) but on a much larger scale and with multiple users. The device is important for HCI research within the school since it embodies the use of direct interaction through touch allowing us to explore the use of natural gestures and affordances to support interaction. It also

uniquely and inherently supports collaborative and co-located interaction. We also host a suite of Android smartphones and Arduino prototyping sensor platforms. They enable us to quickly build technological interventions that go beyond the interaction capabilities of commonly available computing platforms at a low cost and in a wide variety of contexts. The Heritage and Cultural Learning Hub is a collaboration between cross-disciplinary groups including HCI, and consists of just over 500 m2 of space, with a prototyping hall that has infra-red tracking of multiple individuals, including body position and eyegaze, integrated multitouch detection, with full recording and virtual playback of user movement, gaze and interaction within the space and with the technologies. Multiple 3D wall mounted displays, some multitouch, and floor-mounted tables, provide a rich environment for the prototyping and testing of new interactive digital experiences. The Hub is funded with a £1.2m ERDF grant, coupled with matched funding from the University, £150k Garfield Weston Foundation grant, £200k from a philanthropic donor, and other funding. The globally unique Prototyping Hall for user testing multi-touch, multi-user and mobile outputs opened in Summer 2012. The Hall enables the tracking of up to 40 users' movement, gaze and computer interactions, all of which can then be analysed using advanced software, and visually represented in 3D environments.

The medical imaging laboratory, funded by a £60K grant from the AWM (2006) and a further £30k investment from CS's Ramsay research fund (2010), provides significant research capacity for the development of new and novel imaging systems that are designed to maximise the information content of image data. The laboratory houses over £250k of equipment including two optical workbenches, five high-grade scientific cameras, an integrating sphere, two hyperspectral cameras, three liquid crystal tunable filters, a multispectral LED light source, two ocular microscopes, four fibre-coupled white light sources, a 3D printer, and a wide range of general components.

Both our staff members and research students use University's BlueBEAR HPC regularly, which has a peak performance (theoretically) of 848 (cores) * 2.2 (GHz) * 8 (floating point operations/cycle) = 15 TFlop/s. Our strategy in sustaining major infrastructure and facilities is through efficient sharing within and outside the University, e.g., MidPlus Regional HPC Centre (£1.6m from EPSRC and £1.4m from four partners, i.e., Birmingham, Nottingham, Warwick and QMUL).

Seven of our staff are active in consultancies of various kinds. This includes work in human-computer interaction, security, and robotics. The clients include Vodafone, BMW, Walt Disney Corporation, NASA and Roche Pharmaceuticals, as well as a range of smaller companies. In about one-third of cases, such consultancy has led to research publications.

e. Collaboration or contribution to the discipline or research base

We have numerous research collaborations with other institutions locally, nationally and internationally. Locally, for example, we collaborate with Psychology on *the Centre for Computational Neuroscience and Cognitive Robotics*, with EECE (Electrical, Electronic and Computer Engineering) on *the Human-Computer Interaction Centre*, with Biosciences, Mathematics, Medicine and Dentistry on *the System Sciences for Health Initiative*, and with Archaeology on *the Heritage Hub*, in addition to joint grants with Economics, Mathematics, Mechanical Engineering, Civil Engineering and Physics. We are a key partner in the *EPSRC Physical Sciences of Imaging in the Biomedical Sciences (PSIBS) Doctoral Training Centre*, collaborating closely with researchers from Biosciences, Cancer Sciences, Chemical Engineering, Chemistry, Dentistry, Electronic Engineering, Metallurgy and Materials, Mathematics, Medicine, and Physics and Astronomy. *The Midlands Graduate School in the Foundations of Computer Science*, led by Birmingham and supported by EPSRC, has led to numerous collaborations with researchers from the UK and beyond, in terms of joint publications and grant applications.

Nationally and internationally, we also have numerous research collaborations, evidenced by joint publications and funded projects, with both universities and companies in the UK and beyond. We have a formal arrangement with USTC (University of Science and Technology of China) with the establishment of a *USTC-Birmingham Joint Research Institute in Intelligent Computation and Its Applications (UBRI)*. The key expertise of UBRI includes Adaptive Optimisation, Advanced Data

Analysis and Data Mining. It supports an innovative six-year double PhD programme between USTC and Birmingham. In the REF period, we hosted 60+ visiting researchers from 19 different countries, all funded by themselves.

We have **a strong and active Industrial Advisory Board**, with members from: GlaxoSmithKline, HP Labs, Cisco, Juniper Networks, Honda Research Institute Europe, Microsoft, DSTL, IBM, BT, Qinetiq, Object Management Group, Goldman Sachs. Via the Poynting Institute, which is a formal collaboration between the University and Qinetiq, we employ a researcher one day a week from Qinetiq. This has resulted in a number of papers, grant applications, and sponsored studentships. Through joint research projects funded by EPSRC, EU, TSB or industrial partners themselves, we collaborate with BT, Honda Research Institute Europe (Germany), EADS Innovation Works (Germany),STMicroelectronics (Italy), Microsoft, HP Labs, The Supply Guys (USA), Google (USA), Guidance Ltd, G4S, National Nuclear Labs, QinetiQ, and AAF Care Homes (Austria). Such collaborations with our research users have led to patents, tools, joint research publications, or new research grant proposals as a result of discovering new research challenges. **In the REF period, 75+ companies were formally involved in our funded projects (e.g., EPSRC grants).** Interactions with industrialists at different levels have not only influenced our research and staffing strategies, but also contributed to our impact generation and longer term sustainability (through funding). **Our interaction with industry is bidirectional.** Not only did we have industrialists visiting us at the University, we also had staff members seconded to industry, e.g., Ryan and Bordbar to HP Lab, Bordbar to BT, Sorge to Google, etc., through Royal Academy of Engineering's industrial secondment programme or our internal sabbatical scheme. Several staff members are involved in spin-off companies.

Members of staff have played leadership roles nationally and internationally. In the REF period, we gave 71+ keynote/plenary talks and chaired/co-chaired 42+ international conferences. We also had 92+ conference programme committee members. We have had one editor-in-chief, two editors, 13 associate editors, one action editor, and 35 editorial board members of international journals, in addition to nine guest editors of special issues.

We have played active roles in advising various national and international organizations. Barnden was the Chair of SSAISB (The Society for the Study of Artificial Intelligence and Simulation of Behaviour) in 2003-2010 and the Vice-Chair since 2010. Beale was on the Nominet Advisory Panel on Criminal Activity on the Internet (2010-12) and an Honorary Member of the International Advisory Panel of the Institute of Social Informatics and Technological Innovations, Malaysia. Jung is a Member of the (UK) "Computing at School" Network of Excellence overview group. Leonardis was a Board Member of Slovenian Research Agency, Member of the Expert Body (2008-2010), of the European Computer Vision (ECCV) Governing Board, and of the International Association for Pattern Recognition (IAPR) Governing Board. Ryan is an EU-appointed Monitoring Trustee for verifying technical commitments made by ARM Ltd to the European Commission (2013-2018) and a member of the Royal Society International Exchanges Committee (2011-2013). Wyatt was a Member of the UK Ministerial Round Table on Robotics, London, October 2012. Yao is a Member (since 2010) of the Scientific Committee of the European Centre for Soft Computing in Spain, and the President-elect (2013) and the Vice President for Publications (2009-12) of the IEEE Computational Intelligence Society.

Beale is a Fellow of BCS and was a winner of a Royal Academy of Engineering Global Research Award. Claridge is also a BCS Fellow. Dix was elected to ACM SIGCHI Academy in 2013. Garcia won the 2008 I/O Award from the Netherlands Organisation for Scientific Research (NWO) (Dutch research council) for the best outreach of computer science research towards the general public. The selection criteria were clarity of contribution, public outreach, and the quality of the underlying research. Levy was elected a member of the London Mathematical Society, also in 2013. Musolesi and his team won the Data For Development (D4D) Challenge (Best Overall prize) organized by Orange in May 2013 with the submission Exploiting Cellular Data for Disease Containment and Information Campaigns Strategies in Country-wide Epidemics, and the Nokia Mobile Data Open Challenge in June 2012 with the submission Interdependence and Predictability of Human Mobility and Social Interactions. His EmotionSense Project was selected as one of the top 100 innovations of the year 2010 by the independent global agency NetExplorateur. The awards event took place in Paris at UNESCO in February 2011. Musolesi also won the Distinguished Reviewer Award for the

year 2012 for IEEE Transactions on Mobile Computing. Nagaraja won the Faculty Award from Google and X10 Faculty Award from IBM in 2010. Bohnet's work was ranked the first in the 2010 and 2011 Natural Language Generation Challenges, and the first (for English and German dependency parsing) and second (for dependency parsing of all languages) at the CoNLL-2009 Shared Task: Syntactic and Semantic Dependencies in Multiple Languages. Yao won a Royal Society Wolfson Research Merit Award in 2012 and the 2013 IEEE Computational Intelligence Society Evolutionary Computation Pioneer Award. He is a Distinguished Lecturer of the IEEE Computational Intelligence Society, giving the Distinguished "Leon the Mathematician" Lecture at Aristotle University of Thessaloniki, Greece, in November 2010, and three other Distinguished Lectures in Singapore, Melbourne (Australia) and New York (USA) since 2010.

In the REF period, we won more than 23+ Best Paper Awards from international journals and conferences, in addition to one journal spotlight paper and one most notable publication of the year award.