Institution: Heriot-Watt University

Unit of Assessment: Computer Science and Informatics

a. Overview

Our submission characterizes the Department of Computer Science (HWCS) at Heriot-Watt University (HWU). As of November 2013, we number 31 research academics and 41 research staff and are one of the larger units in the Scottish Informatics and Computer Science Alliance (SICSA – www.sisca.ac.uk), with the highest proportion of researchers(1). Our research areas are ***intelligent systems*** **(IS)**, ***interaction*** **(IN)**, and ***rigorous systems*** **(RS)**. Our group structure is shown below, with group leaders in **bold** and with underline to indicate primary group membership.

IS	Biomedical Systems Engineering Lab	**Burger**, Corne, Gray
	Intelligent Systems Lab	**Corne**, Aylett, Burger, Chen-Burger, Gray, Grov, Lemon, Lones, Louchart, McNeill, Rieser, Robertson, N.Taylor, de Wilde, Vargas
	PUMA (Pervasive, Ubiquitous, Mobile Apps)	**N.Taylor**, Gray, McGookin, H.Taylor, Williams
IN	Affective Autonomous Agents	**Aylett**, Louchart, Robertson, Vargas
	Digital StoryLab	**Louchart**, Aylett, Robertson
	Interaction Lab	**Lemon**, Lohan, McGookin, Rieser, Wright-Hastie
	Texture Lab	**Chantler**, Corne
RS	Dependable Systems Group	**Ireland**, Fensch, Gabbay, Georgieva, Grov, Loidl, McNeill, Michaelson, Pooley, Scholz
	ULTRA (Useful Logics, Types, Rewriting & their Automation)	**Kamareddine** Wells

Our structure reflects substantial growth since our RAE 2008 submission (RAE08), and our support for staff to establish new groups in strategic directions. Major post-2008 developments include the Interaction Lab, established with Lemon's appointment in 2009, while PUMA, the Digital StoryLab and the Robotics Lab emerged via staff initiatives coupled with infrastructure investment. Finally, SICSA is a major new factor in our environment, representing ~£1.4M(2) in Scottish Funding Council and HWU investment. Michaelson led SICSA's 'Complex Systems Engineering' theme (one of four themes) from the start, and SICSA funded two staff appointments and seven PhD students, widens our collaboration, knowledge exchange and people development contexts, and provides initiatives we exploit to enhance many other aspects of our environment.

Note(1): Scottish Funding Council data: http://www.sfc.ac.uk/funding/universities/research_funding/funding_research.aspx Note(2): throughout, **financial figures refer to HWCS-only awards and/or the HWCS components of joint awards**, unless clearly indicated otherwise.

b. Research strategy

Vision: We aim to be a leading centre for the development and application of transformative theory and techniques in intelligent, interactive and rigorous systems, especially in large-scale contexts, such as crowd-scale interaction and massively multi-core architectures, while spearheading globally significant applications that exemplify the potential of these areas of computer science.

Relative position in research: 2014 vs 2008: We have grown vigorously, fuelled by investment from HWU in staff (including a net gain of 10 appointments), the Scottish Funding Council (£693k, plus other matching funds from HWU), and accelerating grant success. Our current annual income has almost trebled since RAE08, and 2008-13 spend per FTE is double the 2008 mean for UK Computer Science units. This has driven recruitment (38% growth in submitted staff), PhD scholarships (57 wholly or part-funded 2008-13), and enhanced infrastructure (£1.1m, including £802k secured late in 2013). We have radically increased our funding base in areas that both support our vision and align with global priorities. This includes £6.95m in Human-Computer Interaction (with £560k from recent Digital Economy calls), £1.75m for parallel/multi-core, £1.54m in software verification and £1.28m for pervasive systems. Sustaining future developments, we have also grown external industry and academic collaboration (evidenced throughout REF5 and REF3a), and are starting to establish profile in further global priorities such as energy and

healthcare, for which 2008-13 awards total £612k and £255k respectively.
Broad Strategy for growth of HWCS research: Our strategy in the current period (unaltered from RAE08) had five strands: 1. *investment in new opportunities and existing areas of strength*; 2. *broader industrial activity*; 3. *wider UK and international collaborations*; 4. *increasing research student numbers*; 5. *strongly supporting early-career researchers*. We drew on several aspects of our 2008-13 environment to help realise these goals in the current period. In particular: 1. SICSA provided mechanisms to help grow and enhance our environment; 2. HWU established initiatives stressing strategic academic growth and interdisciplinary interaction; 3. with new HWU senior appointments (Miller, 2009, PVC Research, Neiland, 2010, Scottish Crucible Programme leader), provision for researcher training was reinvigorated; 4. the national context saw the emergence of the Digital Economy theme and reshaping of EPSRC's approach to ICT, while both national and international sponsors increased their emphases on the Digital Economy and Energy. Exploiting aspects 1-3 and our own initiatives, significant progress has been made on all broad strategy points (evidenced in the relevant sections herein), while aspect 4 influenced detailed strategy. We now elaborate our **2008-13 strategy, achievements and plans** in relation to our main areas.
Intelligent systems: we aim to transform the quality and potential for large scale optimization, robot control, decision-making, and pervasive computing, by drawing on inspiration from nature and via new synergies among machine learning, optimization and complexity science. Our work is underpinned by distinct approaches. For example, Corne combines machine learning with optimization in novel ways to accelerate large-scale optimization; De Wilde draws inspiration from neural/vascular networks for robust decision systems; Vargas draws on mammalian homeostasis mechanisms for robot control architectures. Our **Strategy 2008-13** has been to widen both academic and industry collaborations around these threads, to find new contexts and applications to explore and exploit our ideas. **Evidence of achieving aims 2008-13:** we have won 13 projects with industry collaborators (£1.24m), largely developing new ideas for large-scale and multi-objective optimization in BAE Systems, BP, Motorola, Renishaw, and four SMEs; several of these projects involved HWU geologists and engineers. Academic and industry collaborations are further exemplified by two EU FP7 awards in the pervasive systems area - PERSIST (2008-10) and SOCIETIES (2010-14) - totalling £1.28m to HWCS from £14.2m total EU contribution. These respectively established the concept of a *personal smartspace*, and then extended this to the idea of a *community smartspace*, together involving four academic and twelve industry collaborators including IBM, Intel and NEC, and developing underpinning technology that will enable intelligent, context-aware, personalised systems to transform how we work, communicate and socialise. Further collaboration includes Burger's work with the MRC Human Genetics Unit (4 awards, £443k), contributing to his plans with Baldock (Edinburgh) to set the agenda for biomedical atlases in the life sciences (Burger outputs 1 and 2). Finally, two of Vargas' outputs on novel robot control architectures have won prizes (a journal contribution award for Vargas output 4, while Vargas output 1 extends an IEEE Conference 'best paper'). **Future plans** centre on bringing our ideas to bear on major societal and environmental challenges, by further growing external collaborations in energy, environment, and healthcare, and working together at the interface of human/robot/avatar interaction and pervasive systems. Recent activities reflecting these plans include: (i) collaboration (2012) with HWU's School of the Built Environment and six EU partners in the FP7 ORIGIN project (2012-15, £287k (£2.8m total)), which is exploring learning/optimisation in smart metering; (ii) the 'Robotarium' EPSRC capital award (£7.2m to HWU and Edinburgh in late 2013, our part of which is £802k in multimodal interaction, high-performance computing, and robotics equipment), which will underpin new collaborative ventures between all of our areas as well as turbo-charge new external interactions; (iii) HWCS allocation (2013) of an EPSRC DTA student to Vargas in adaptive rehabilitative robotics in collaboration with a health scientist at Q. Margaret U.; (iv) crowd-funding ($11k from 254 funders worldwide), plus further equipment for HWU's Ocean Systems Lab via Robotarium, to support Corne's ideas for computational intelligence in marine conservation.
Interaction: Our mission in this area is to enable future intelligent interactive systems that can collaborate effectively and adaptively with humans, using a full variety of modalities, for application areas including mobile search, enhanced learning, healthcare, human-robot interaction, and supporting collaboration and creativity. The **strategy of the Interaction Lab** is to combine statistical and symbolic information processing, using data-driven machine learning to build robust agents that can adapt autonomously under uncertainty. In 2008-13 the interaction lab focused on multimodal dialogue, supported by advanced probabilistic techniques in modelling and planning,

thus handling uncertainty in interactions and improving the effectiveness of human/machine interaction. **Evidence of achieving aims 2008-13:** The Interaction Lab won 8 awards totalling £2.92m (from ESRC, EPSRC, ERC and EU FP7) to develop the enabling probabilistic techniques, and apply them in scenarios ranging from mobile spoken dialogue systems (such as Siri), to multimodal interfaces for autism, healthcare, and social robotics. Achievements include novel theory and applications of reinforcement learning to Natural Language Generation and robust spoken dialogue management, data-driven techniques enabling rapid generation of multimodal interfaces for new applications, virtual characters for communication skills learning in autism, advances in socially intelligent robots, and new models of non-cooperative dialogue. Meanwhile, the Affective Autonomous Agents Lab and Digital StoryLab explore novel modes of interaction, with an emphasis on interactive virtual characters and graphical environments, towards transforming the uses of computers in society and education. Following their development of novel human-like memory models to underpin human/robot and human/avatar interaction, their **strategy 2008-13** was twofold: (i) to further develop and capitalise on these models in important social contexts; (ii) to extend the theory, models and platforms from individual towards social interaction. **Achievements 2008-13** include three EU projects (total £1.68m), which developed the first humanlike memory models for virtual characters and social robotics, and explored technology enhanced education aimed at intercultural understanding. Additionally, three EPSRC awards (£551k) explored collaborative research spaces and the associated social interactions, and developed new understandings of the relationships between users, media and narratives, while **Robertson's** EPSRC Partnership for Public Engagement grant (£100k) and EPSRC Impact Acceleration Account (IAA) award (£42k) are building on her work to enhance creativity in education, via implementation in schools and with the wider public. Finally, the **strategy of the Texture Lab 2008-13** has been to build on insights and techniques from pre-2008 research (primarily aimed at how humans recognize and browse textures) in two ways. First, to support new ideas for the Digital Economy, facilitated in part by **Chantler's** leadership of the 'Digital Tools' theme in HWU's EPSRC funded James Watt Institute for High Value Manufacturing (JWIHVMEPSRC; £7.1m 2008-13, Chantler is co-I). Second, to bring those insights to bear on how humans might navigate and grasp large complex text, speech and image collections, thereby supporting collaboration, creativity and design more widely. In addition to a best-paper award at www.asmeconferences.org/congress2013 for the latter work (supporting engineering design), **achievements 2008-13** include 5 awards from the JWIHVM (£823k), the EPSRC ICT Perspectives project (£187k, 2012-14) to support collaboration via browsing the Grants on the Web project text corpus, four further RCUK Digital Economy projects (£553k) and £39k from HWU's EPSRC IAA, (plus £30k matching cash from Skanska plc) for intelligent organisation and browsing of corporate meeting archives. **Future plans** in interaction include increasingly developing and applying enabling technologies in larger scale social contexts. For example, the Interaction Lab plans to explore and demonstrate robust multimodal interaction in group contexts, while the Autonomous Affective Agents lab (with colleagues in intelligent systems) plan to merge the concepts of socially-aware virtual characters and social robotics with pervasive and ubiquitous systems, towards developing new frontiers and platforms for virtual characters and social robotics in large-scale pervasive social computing environments. These plans are facilitated by the Robotarium award (see towards end of page 2), as well as a late-2013 IAA award to **Rieser** (£50k with $30k matching from Berkeley's International Computer Science Institute) that will demonstrate natural location-aware dialogue in a Siri-style spoken-dialogue system.

Rigorous Systems: Our research in this area tackles the fundamental modelling and language design challenges that underpin safe, reliable, verifiable, flexible and high-performance software engineering practices and systems over arbitrary architectures. The Dependable Systems Group (DSG) improves the reliability and predictability of computer systems through the development and application of rigorous design, implementation and verification techniques. Their vision sees a future in which safe, reliable, resource-aware and resource-costed computation is available and achievable over arbitrary and dynamically changing architectures. DSG's strategy is to realise this vision via research into high-level language concepts and associated compilers/interpreters, thus enabling solutions (e.g. costed parallel compilation) usable in arbitrary existing contexts (e.g. C, Java), with no need for users to adopt a new language. **Achievements 2008-13** include the EU FP7 project RELEASE (£472k, 2010-13) to develop high-level solutions for future reliable massively multi-core systems, and three EPSRC projects (£148k, 2008-11; £365k, 2013-16; 679k,

2013-18), which respectively (i) developed verified, resource-aware, costed approaches for image processing applications; (ii) build on this to develop automated generation of ultra-fast bespoke image processing systems over reconfigurable architectures, and (iii) will automatically transform parallel programs to run effectively on heterogeneous, many-core systems with formal guarantees of correctness. A further major thread of DSG's strategy is to bring formal mathematical reasoning techniques, in particular proof planning and associated developments in artificial intelligence, to bear on software verification. **Evidence of achievements 2008-13** includes **Ireland's** EPSRC Platform Grant (£1.14m 2011-15), with partners at Edinburgh and Imperial/Goldsmith's, which underpins on-going strategy to deliver approaches to software verification that can apply to larger scale systems and facilitate their adoption in industry. **Future plans** are to capitalise on academic and industry collaboration initiatives and further basic research, to realise large-scale software verification and transform the accessibility of arbitrary high-performance architectures. Facilitators for this include on-going community workshops (established by **Ireland'**s part of the 'AI4FM' EPSRC grant, £23k, 2011-14), exploratory project-funding devices within the Platform grant, and Scholz's part of the 'Robotarium' award that includes £174k in new High-Performance equipment. Alongside this, **Gabbay's** foundational work in nominal logics is seeking to revolutionize how computer science handles names, and in the current period this has been supported by a Leverhulme Fellowship (£45k). Accelerated by this, his research achievements have led to a range of invited talks (including Cambridge, Oxford, and Tel-Aviv Universities) and new collaborations. Finally, the foundational language theory research of both **Kamareddine** and **Wells** continued to establish novel results at the intersection of types, logic and semantics, in particular in expansion.

c. People, including:

i. Staffing strategy and staff development

Academic staffing strategy: Our broad strategy is to aim for sustainable growth, via a healthy and robust balance of senior and early-career staff, and theory-oriented and application-oriented groupings; since each of these directions maximises our agility in the face of shifting priorities, opportunities, and rapid developments in computer science and its interfaces. Detailed staffing strategy during 2008-13 has extended this in two ways: (i) to grow and achieve these balances (hence strengthening sustainability) in each of our three main areas, and (ii) to increase the numbers of early-career staff who straddle two or more of our areas, and hence underpin future larger-scale research programmes. With details below, 2008-13 **achievements** are evidenced by a net gain of 10 staff members via 14 new appointments (3 mid- and 11 early-career), aligning with our distinct strengths, UK and international priorities, and in areas that help realise our vision. (Of four RAE08 staff who left in 2008-13, only one joined another Computer Science unit, while one retired, one moved to industry (Netherlands), and one passed away.)

In **intelligent systems**: **Vargas** (appointed as early-career, 2009) brought expertise in autonomous robotics, and catalysed the establishment of our Robotics lab, the ensuing equipment provision (see section (d) facilities), new links with Brazilian institutions, and increasingly fruitful collaborations between HWCS, and HWU's School of Engineering & Physical Sciences (EPS). This has led to our co-organization of EPS' MSc in Autonomous Robotics, and our part (also via Aylett, Wright-Hastie, Lemon, Scholz, N.Taylor) of the Robotarium award. Meanwhile, **Chen-Burger** (mid-career), **Gray**, **Lones**, **McGookin** and **McNeill** (all early-career) were appointed in 2013**. Chen-Burger** brings leading expertise in knowledge engineering, particularly regarding enterprise, process and workflow modelling, along with a decade of experience gained at Edinburgh's Artificial Intelligence Applications Institute**. Gray** and **Lones** respectively (i) strengthen our portfolio in semantic web and databases, as well as bring expertise in sensor networks and strong links with Manchester, and (ii) bolster our capability in novel emergent computing techniques and their applications in health and robotics. McGookin widens our pervasive and mobile portfolio with interaction design for disabled users, establishes a strong link with Glasgow's interaction research group, and widens links between our intelligent systems and interaction areas. Finally**, McNeill** brings a track record in formal reasoning under uncertainty and disaster response management to bridge to our intelligent and rigorous systems areas. In **interaction**, **Lemon** (mid-career) was a SICSA-supported recruit in 2009, establishing our Interaction Lab and significantly raising our profile in this area (see section (b)), while helping us attract further appointments into this group (all early-career), namely: **Wright-Hastie** (2010) and **Rieser** (2012) from Edinburgh, and **Lohan** (2013) from Bielefeld (Germany), via Genoa (Italy). **Wright-Hastie** and **Rieser** bring unique approaches at the interfaces of machine learning, probabilistic reasoning and dialogue, and have

advanced the Interaction Lab's research and knowledge exchange aims: Wright-Hastie is PI of EU FP7 PARLANCE (£750k, 2011-14) spearheading techniques for spoken dialogue systems in open domains and interactive search, while Rieser has synchronised Interaction Lab research with industry leaders Nuance Inc via a HWCS-supported leave of absence (see REF3a). Lohan adds leading expertise in the theory and practice of gesture-based human-robot interaction. In **rigorous systems**, **Loidl** joined us in 2009 as a SICSA-supported recruit, and has catalysed and sustained several collaborative research ventures furthering multi-core research within SICSA and beyond (details in section (d)). The appointments of **Scholz** (2011), **Grov** (2012) and **Fensch** (2013) followed (early-career, except Scholz), each broadening our footprint in parallel computing. **Scholz** brings unique expertise in parallel compilation (currently funded by his 2013-17 £673k EPSRC award). **Fensch**, a Royal Academy of Engineering Fellow (2011-16), further grows our links with Edinburgh and adds leadership at the hardware/software interface. Finally, **Grov** bridges intelligent and rigorous systems, is a Co-I of Ireland's Platform grant; and brings machine learning ideas to software verification, which we believe are key in enabling verification of large-scale systems.

People Support and Development: We enable and support all staff and students' research ambitions by providing a relentlessly 'can-do' environment, maximising access to space, time, training, funds and facilities. People can travel when needed (e.g. to sandpits, conferences, EU information days), and we waive bench fees for research visitors. Our 2008-13 support for staff and student incidental travel has benefited the great majority of our staff, while all of our early-career staff (those in post for at least a semester) have benefited from significant time in training, research visits abroad, or both.

Evidencing effectiveness: travel support has enabled Aylett and Chantler to attend EPSRC sandpits, leading to six EPSRC awards (£1m), and enabled Vargas' visits to robotics labs in Brazil (2010 and 2013), leading to an exchange programme, joint PhD arrangements and (so far) two research visits from Brazilian scientists. **Concerning training**, the main mechanisms available in 2008-13, to which we later refer, are tabulated below:

Provided by SICSA
Research theme workshops, Distinguished Visitors Programme, SICSA Seminar programme
Provided by HWU 'Research Futures' unit
Postgraduate Certificate in Academic Practice (PGCAP - focus on early-career staff)
Researcher Development Programme
Learning Enhancement And Development Skills (LEADS) courses
Scottish Crucible, and HWU Crucible Programme (focus on academics and RAs)
Provided by HWCS
Research Day - annual awayday, with talks on current strategy, grant-writing, posters and
HWCS and Group Seminar Programmes

Further examples of people development serving strategic aims (2008-13): Each of Burger, Corne (mid-career), Dethlefs (RA), Loidl, Louchart and Vargas (early-career) have attended the six-day HWU Crucible programme, while Crook (RA), Wright-Hastie, Louchart and Rieser (early-career) have also won (competitive) places at the Scottish Crucible programme. Five of these nine staff won seed funding for interdisciplinary projects as a result. One of Corne's seed projects (2012) involves marine biologists and roboticists at HWU and has gained global coverage (including BBC World Service radio, Canadian TV, BBC Technology website, The Scotsman newspaper, and many more) and consolidated links with Lane (EPS, Ocean Systems Lab), and joint bids with overseas academics, including Dorigo (Brussels). One of Rieser's two seed-fund projects is exploring how computer games can encourage environmentally friendly behaviour, integrating psychology, education, visualisation and social science. The other is exploring how interactive systems can transform support in medical emergencies, integrating cognitive neuroscience, language processing, sociology and medical expertise. These projects grew Rieser's collaborator network with scientists in various disciplines from six universities.

Scholarships allocation: We build on the EPSRC DTA with HWCS funds and agility to provide studentships in support of staff development. Examples include five studentships in 2011/12, organised as part of an HWCS business case for a Distance Learning initiative, two EPSRC Industrial CASE students in the period (Motorola and BAE Systems), our seven SICSA-supported studentships, and seven won competitively through HWU schemes (one in 2010, one in 2011,

three in 2012, two in 2013). Meanwhile 36 other studentships 2008-13 have been part-sponsored by us via a variety of means. Our approach to allocation places high weight on supporting new staff members currently without PhD students. For example, in 2008-13, Loidl, Louchart, Rieser and Vargas (all early-career) were awarded students from our DTA or from internal schemes.
Visiting/International staff: Our strategy is to widen our engagement with world leaders in areas that overlap our interests, and/or help us better engage with global priorities. Examples 2008-13 include: Aizenburg (Texas A&M U., pioneer in multi-valued neural networks), Berthold (U. of Copenhagen, leader in parallel programming), Harris (Oracle Labs, Cambridge, industry leader in distributed runtime systems), Sim (Hong Kong, cloud computing), and Williams (Microsoft Research, Washington, leader in dialogue management). Visitors are especially encouraged in areas relevant to our early-career staff. For example, the visits by Berthold and Harris were organized by Loidl with SICSA support. Other examples include Johnson (Kent, three months), Pessin (U. São Paolo, twelve months), Couceiro (U. of Coimbra, three months), and Oliveira (Federal U. Uberlândia, Brazil, eleven months), all visiting Vargas' robotics lab.
Implementation of the Concordat for Researcher Development (CRD) is exemplified in the training provision tabulated in this section, and HWU's commitment to the CRD is also reflected in our 'HR Excellence in Research' accreditation by the European Commission in 2010 and 2012. The tabulated initiatives focus on CRD Key Principles 2-5 (valuing, supporting, and developing researchers), which are also championed in HWU's Performance & Development Review process, comprising maintenance/review of personal development plans and regular review discussions. We achieve CRD Principle 1 – recruiting, selecting and retaining the best – in part by ensuring vacancies are advertised globally, and via agile contract bridging (e.g. funds from Ireland's Platform grant partly used for bridging have benefited contract researchers at each of HWCS, Edinburgh, Imperial and Goldsmith's). High-level monitoring and review (CRD Principle 7) are achieved by regular staff survey and data collection (e.g. registration data for career development courses), and similar activity also supports our regular 'HR Excellence in Research' accreditation. Regarding CRD key principle 6 (equality and diversity): HWU holds an Athena SWAN Institutional Bronze award, and HWCS is the 6th closest to gender equality in academic staff numbers of 103 Computer Science units in the UK (based on latest available HESA data, 2011/12). This aids our efforts to ensure selection panels, boards and committees have mixed gender, and we routinely make whatever arrangements are needed to accommodate staff circumstances. For example, in 2008-13 five staff had parental leave of whom two were subsequently promoted.

ii. Research students

Our PhD awards per FTE has improved 28% since RAE08 (based on staff in post before August 2013). This reflects a range of initiatives and achievements in recruitment (including SICSA Prize studentships and other schemes mentioned above), and in training. The mechanisms in the table on page 5 (aside from the Crucible) are all open to research students, while below we list additional training provision and activities solely for, or focussed on, our research students.

Provided by SICSA
Annual SICSA PhD Conference, Regular themed Summer Schools, cross-site supervisors
Provided by HWU 'Research Futures' unit
Annual Postgraduate Conference (organised and run by HWU postgraduates)
Provided by HWCS
Laboratory Open Day – annual open day to coincide with visit of Computer Science Industry Steering group; every PhD student provides a poster and (if appropriate) a demo.
Research student seminar programme (organized and delivered by our PhD students)

We use these mechanisms to build on a backbone of regular monitoring and arrangements within individual student/supervisor teams, aiming to ensure a stimulating and collaborative programme for all of our students. The standard experience for an HWCS research student whose studies were within the 2008-13 period included: nine training-oriented conferences and workshops, three academic conference trips (incl. one overseas), three internal presentations, three internal vivas, three poster sessions with industry and academic audiences, two summer schools, and four short training courses. Examples of engagement include students Totoo and Belikov, who respectively co-organized the 2012 and 2013 SICSA PhD conferences, while almost all of our 2008-13 students engaged in either SICSA training, HWU Research Futures training, or both (and all engaged in the HWCS mechanisms). In addition, several of the knowledge exchange mechanisms described in

REF3a are student-centred. Evidence of effectiveness in our approaches to student development (in addition to examples provided in REF3a), includes: (i) best paper prizes for Lohpetch (2008), McBurney (2008). Chantar (2010), Liano (2011); (ii) an IBM PhD Internship award for Vallejo (2013) supplemented by a SICSA Industry Internship award; (iii) a Google PhD internship award for MacVean (2013); (iv) notable destinations of our 2008-13 PhD graduates include Gallacher (née McBurney - Senior RA at Intel Collab. Research Inst. for Sustainable Connected Cities), Kriegel (Software Engineer at Toshiba Medical Visualization Systems), Liano (RA at Imperial) and Rahli (postdoc at Cornell), while two of our recent staff recruits are HWCS PhD graduates: Grov (via postdoc at Edinburgh), and Gray (via postdocs at Glasgow and Manchester).

d. Income, infrastructure and facilities

Portfolio 2008-13 and future plans: Our funding portfolio by area is below. Complementing data in REF4, we show totals for projects that started or were awarded between 01/2008 and 07/2013. Only the HWCS component is given, shared equally when multiple HWCS areas are involved. We show in parentheses a comparison with the indicative corresponding figure for 2003-07.

Research Area	RCUK	EU	TSB/Industry/charity
Intelligent systems	£526k (up 310%)	£1.82m (up 230%)	£921k (up 550%, mainly TSB)
Interaction	£2.91m (up 370%)	£4.31m (up 850%)	£67k (up 25%) – RSE Fellowship
Rigorous systems	£3.2m (up 710%)	£533k (dn 10%)	£96k (dn 75%)
Totals	**£6.65m** (up 480%)	**£6.66m** (up 360%)	**£1.1m** (up 86%)

Each area has seen an increased rate of awards overall, reflecting sharp growth from pre-2008 submitted staff (£9.3m – 2.6-fold rise in awards p.a.) as well as successes from post-2008 recruits (£4.1m). This period's acceleration in each of EPSRC, EU and other funding (mainly TSB, charity and industry) has been assisted by consolidation of our national and international collaborator networks. Our future planning involves building on that to further raise our profile in consortia delivering exciting and substantial interdisciplinary proposals to both RCUK and the EU. Some specific areas for such proposals will be (i) to develop computational intelligence applications in rehabilitative robotics, marine science, and renewable energy futures; (ii) to develop further multi-modal, creative and robotic systems for social media, edutainment, serious games, and a wide range of societal applications in education and e-health; (iii) to achieve the necessary research advances and breakthroughs we need to bring verified software to large scale systems and to industry as a whole. We plan to achieve some of these aims by broadening our funding sources to include more Fellowships, and by developing more alliances with specific organizations and academic/industry consortia. For example we are currently in discussion with the British Geological Survey (moving to HWU campus in 2015) around transforming their use of High-Performance Computing (HPC), and consolidating their current and future HPC procurement with ours, as well as a variety of joint research programmes in climate, energy and large-scale data analytics.

At the level of research areas: Research in **intelligent systems** has been supported largely by EU and by application-oriented funding sources. We plan to raise RCUK funding levels in the future partly on the basis of research ideas emerging from current applied projects, and also by exploiting the wider and further consolidated collaboration base gained via recent appointments in this area (Edinburgh, Manchester, York). Both **interaction** and **rigorous systems** have substantially raised their RCUK funding profiles and **interaction** has also considerably raised its EU profile; both areas are currently (broadly speaking) at the cusp of turning a large body of foundational research into impact, and plan to raise levels of TSB/Industry activity in the coming period. These plans are supported by, for example, a current EPSRC CASE studentship with BAE Systems (student Murali is working directly with the Astraea unmanned aircraft design team), and the impact plans for in much of their current EPSRC and EU portfolio in these areas (involving, for example, Codeplay, Maxelier Technologies, Rolls-Royce, Skanska, and Yahoo). Future plans in all areas, especially for cross-area interaction, are also boosted by our part of the Robotarium award (see end of page 2), including £174k for a new High-Performance Computing cluster and £628k for multimodal interface and expressive robotics equipment. Finally, 12 HWCS staff are part of the bid/supervisor team that was awarded an EPSRC Centre for Doctorial Training in Robotics and Autonomous Systems in late 2013 (CDT-RAS – HWU/Edinburgh). CDT-RAS will support 65 students, fuelling our efforts from 2014 onwards in regard to all broad strategy points.

Infrastructure and facilities: We occupy contiguous space across three floors of the large 'Earl Mountbatten' building (EMB) at HWU's main campus. Since 2008 two significant new spaces have

entered our environment: (i) HWU's £9m Postgraduate Centre (PGC), opened in 2010, adjacent to us, and housing lecture, seminar, study and social spaces, and advanced video-conferencing facilities. The PGC hosts our annual Research Day, and many of the academic and technology transfer events we host; (ii) Following £60k institutional investment (2009/10) to refurbish an area of EMB, HWCS won £110k from SRIF funds (2009/10) to provide interactive computing kit and further refurbishment of this area, now called the Learning Zone, which is becoming a research and demonstration area for pervasive, ubiquitous and mobile technologies (a 'smart space'), as well as a meeting area for all students and staff. Finally, space arrangements for our portion of the 'Robotarium' equipment will result in a new Lab, Robotarium West, with 24hr audio/video connection and equipment control interfaces with the sister Robotarium East Lab at Edinburgh. **General computing resources**: All groups have their own Labs containing up to date hardware and software relevant for their research, either won from grants or provided by HWCS for pump-priming. Labs substantially resourced in this way include one for each of the groups in our interaction area, along with the Dependable Systems Group, PUMA, and the Robotics Lab. Investments since 2008 have consolidated our HPC capability and pump-primed growing cross-group interests, while stressing development of early-career staff. These include (i) £50k in HPC infrastructure, which has doubled since 2008: we now have a 256 core Beowulf cluster comprising 32 nodes each with eight Intel 5506 cores; (ii) £50k to inaugurate the Robotics Lab (2010), to support new teaching and continuing research in autonomous intelligent robotics and human-robot interaction (4 Nao robots, 20 e-Pucks, 10 Webots licenses, and a Robot Arena meeting IEEE-FIRA robot cup competition spec.); (iii) Following HWU's award from EPSRC's Small Equipment initiative, HWCS purchased £18k of kit, including an Intel Xeon Phi co-processor and further equipment for the Robotics lab, synchronising our facilities with Vargas' key UK/EU collaborators. Finally, our SICSA award (£1.38m in total – see part (a)) has supported Lemon and Loidl, seven PhD studentships, and partial HWCS staff time for a wide range of SICSA activities. Further significant institutional support is evident in our net gain of 10 research academics in this period.

e. Collaboration or contribution to the discipline or research base

We coach staff to be entrepreneurial in contributing globally to our discipline and others. Examples below are organised into four categories, although often the activity embraces multiple categories. **Leadership: Ireland** chaired 'Verified Software: Theories, Tools and Experiments' (VSTTE 2010), the flagship conference of the Verified Software Initiative (VSI) - a 15-year international project directed at the scientific challenges of large-scale software verification. Ireland built on this to drive the VSI agenda forward by incorporating new knowledge-exchange activity, including the setup of a Microsoft Verified Software Milestone Award administered by us. Other 2008-13 chairing of significant events in our areas include IFL 2008 (Implementation & Application of Functional Languages, Scholz), Information Systems Development 2011 (**Pooley**) and the UK Workshop on Computational Intelligence 2012 (de Wilde), while Programme chair and similar roles included SIGDIAL (2010), IEEE Symp. on Comp. Biology and Bioinformatics 2013, and the IEEE/ACM Conf. on Automated Software Engineering 2013. Editorial board roles on key journals in our areas include: the ACM Trans. on Interactive Intelligent Systems, ACM Trans. on Speech and Language Processing, Applied Logic, Evolutionary Computation, IEEE Systems, Man and Cybernetics, Journal of Biomedical Semantics, Natural Computing, SpringerPlus, The Computer Journal, and Theoretical Computer Science. Meanwhile, each of **Corne, Ireland** and **Scholz** sit on international standards committees (resp. IFIP working groups on computational intelligence, software verification and code generation). Nine of us are members of the EPSRC College, and two early-career staff (**Wright-Hastie, McNeill**) were selected as members of the Royal Society of Edinburgh's Young Academy. **Chantler** is a member of the EPSRC Strategic Advisory Team for ICT, and on the Programme Advisory Board for RCUK's Digital Economy theme, and Corne is on the Royal Society's International Networks Committee (2010-15). Other notable positions include **Rieser's** board membership (one of five) of the Association for Computational Linguistics (ACL) Special Interest Group on Natural Language Generation, along with her position (with five others) on the Scientific Advisory Committee of SIGDIAL (Special Interest Group on Discourse and Dialogue). Further international leadership 2008-13 includes **Georgieva's** recent appointment by the European Commission to the Horizon 2020 Marie Skłodowska-Curie Advisory Group (she is one of only 22 members from across Europe), while several of us have participated in overseas Computer Science funding panels (including EU, Ireland, Finland, Sweden, and UAE), and further international proposal reviewing.

Collaboration with the academic and user bases: Loidl co-ordinates the 'SICSA multi-core challenge' (http://is.gd/MCORE), engaging academic groups in parallel computation around a set of agreed benchmark programs for parallelisation across (networks of) multi-cores. **Grov** organised a two-day SICSA Summer School on Formal Representation and Reasoning for Complex Systems at VSTTE 2010, including four overseas presenters, inspiring what is now a regular VSTTE event. Further major collaboration with the academic base has sprung from our 'ICT Perspectives' EPSRC Network grant (£187k, 2011-14). The aim of this work is primarily to support the research community's understanding and interaction with the EPSRC ICT portfolio via text analytics and related tools, while also exploiting those tools for targeted workshops and discussion events. Outputs from this work – in particular an approach to generating a fair and sound crowd-sourced thematic overview of a research area – were used in the EPSRC ICT 'Towards an Intelligent Information Infrastructure' (TI3) theme meeting at Birmingham (2012). This led directly to shaping the TI3 web presence and the EPSRC TI3 call for proposals in 2013. In the same way, the ICT Perspectives project enabled the June 2013 workshop of the EPSRC £1.5m 'New Economic Models in the Digital Economy' (NEMODE) network to yield community driven definition of the Digital Economy landscape and research priorities, directly shaping NEMODE's call for proposals to distribute £1m of research funding from late 2013. Finally, representing accelerating adoption for the ICT Perspectives tools, they are due to be exploited in early 2014 as part of three EPSRC meetings to scope heathcare technologies research. HWCS staff maintain many substantial and focussed interactions with academics in the UK and globally. Current EU projects alone include 39 academic and 20 industry partners. Academic collaborations (with substantial outputs 2008-13) include **Gabbay's** with Nanevski (UPM, Madrid), Dowek (INRIA), Kropholler (Maths, Glasgow), and Mathijssen (Eindhoven); Kamareddine's with Rincón (Brazil) and Naur (France); **Michaelson's** with Sérot (U. Blaise Pascal), Cole (Edinburgh), Hammond (St Andrews) and Cockshott (Glasgow) and **Vargas**' with Husbands (Sussex), and Freitas (Kent).

Examples of user base interaction to inform new research directions: **Chantler** regularly engages with the James Watt Institute for High Value Manufacturing's industry workshops specifically to identify research needs - one recent outcome is engagement with Skanska, who provided £30k cash in support of an EPSRC IAA award (£50k) to investigate concept browsing from recordings of design meetings; another is the award of an EngD studentship with Rolls Royce, Derby, for automated detection of defects from images. Meanwhile, in a partnership arising from his plenary talk at IEEE WCCI 2008, **Corne** won a SEAS DTC award (£54k. 2010-11) with Waldock (BAE Systems) to explore how combining multi-objective search with the new 'probability collectives' optimisation paradigm might address certain of BAE Systems' future strategies for dealing with large-scale systems design projects, (which included adoption of SysML). This led to a patent and five joint publications, one of which establishes how SysML (systems-oriented XML) can be exploited to cast large scale optimisation problems in a way that makes them amenable to accelerated optimisation strategies (a concept that emerged and developed in this interaction).

Interdisciplinarity: Support for interdisciplinary interaction is vital in our strategy, since it clarifies and extends research questions, widens the opportunities to win funds to answer these questions, and broadens the experience and impact of our people. We briefly note some exemplars not given elsewhere. **Chantler** leads HWU's 'Creativity, Design and Innovation' (CDI) theme, which supports joint projects involving academics across HWCS, and HWU's School of Textiles & Design (SoT&D), and Management and Languages. **Aylett, Louchart** and **Chantler** each won CDI studentships jointly with SoT&D, respectively exploring the integration of smart costumes with pervasive computing, and crowdsourcing for visual co-design. **Louchart** works with Lim (UoA B15) on new frontiers for 'serious games' in the context of engineering design (Louchart output 1), and with Maniscalco (Physics) on gamification to explore research questions in quantum physics (DOI:10.1007/978-3-642-40790-1_17); these interactions emerged from Louchart's time on the Scottish and HWU Crucibles. Finally, **Burger** works with Edinburgh's Institute of Genetics and Molecular Medicine (IGMM), having been seconded to IGMM at 60% FTE until mid 2013. This has helped define Burger's vision for personalised medicine which will in part be pursued in future by collaboration with HWU's Institute of Biochemistry, Biophysics and Bioengineering.