

Institution: Birkbeck, University of London

Unit of Assessment: UoA 11 Computer Science and Informatics

Title of case study: Research advances in Participatory Cyber-physical Computing resulting in innovative applications in Monitoring Biodiversity, Healthcare, Urban Development, Transportation and Art.

1. Summary of the impact

Research undertaken between 2002 and 2012 at Birkbeck has helped establish a participatory approach to cyber-physical computing as the predominant methodology for the construction of mobile and pervasive computing systems. Cyber-physical systems intimately interlink material entities and their information representations as existing on the Internet. Our specific research contributions in systems architecture, privacy protection and human dynamics have demonstrated how the user's activity can be exploited as the core ingredient in building such systems. Our research has resulted in the implementation of applications that are used to monitor biodiversity across the globe, to assess and support Parkinson's disease patients in the UK, to improve the well-being of office workers in London, to engage the public in a debate about the costs and benefits of pervasive computing, and to inform legislatures in the UK and the US.

2. Underpinning research

Sustained advances in microelectronics have enabled the integration of miniaturised information-processing and communications devices into a wide range of physical objects. This enables direct inter-linking of material entities and their information representations as existing in the Internet. In recent years, a range of approaches have been proposed for the design and development of pervasive computing systems, for example Ambient Intelligence, Smart Dust and the Internet of Things, each giving priority to different concepts and adopting distinct viewpoints.

The Pervasive Computing group at Birkbeck has pioneered *Participatory Cyber-physical Computing* as a distinct methodology for the construction of mobile and pervasive computing systems, starting from the premise that users and their actions are an integral component of such systems. In our approach, patterns of users' behaviours dynamically steer the systems' operation, enabled by data gathered through one or more personal devices, such as mobile phones, and supported by distinct software architectures. Since these mobile and pervasive computing systems transparently capture users' behaviours, they also offer a method of observation and measurement of human dynamics, including patterns of individual and social interaction.

Our research has made specific contributions in three key areas:

Systems Architecture: Our research on networked radio-frequency identification (RFID) addresses the unique requirements of pervasive computing systems at scale, specifically the very high velocity of unique item observations, and the prominent role of edge networks that provide entry points into enterprise core systems. We establish a multi-level sensor observation-processing pipeline for the transformation of raw observations into meaningful events and the separation of concerns between edge and core. This work supplies the blueprint for the design of the current generation of RFID-based enterprise resource management platforms [6]. Exploring further the relationship between cyber-physical systems and mobile networks, our research identifies effective and efficient mechanisms to support users' authoring, sensing, and software orchestration in pervasive computing systems, including the participatory methodology introduced in [2] and location-aware information transcoding, delay tolerant communication strategies and service composition in low-power personal area networks highlighted in [4].

Privacy protection: Our research on RFID also identifies the multiple ways in which user control must be exercised over such systems in order to compensate for their unsupervised and transparent operation, and specifically quantifies the trade-off between privacy, functionality and

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rewards [5]. We relate these findings to ethics and legislation with a view to increasing the acceptance of pervasive computing systems by the general public [4].

Human Dynamics: Participatory approaches inevitably lead to the collection of detailed records of human activity. Our research identifies a coherent set of attributes computable from such records that capture its dynamic properties and we employ these as the foundation upon which to construct abstract models of individual and social behaviour and to undertake inferencing via machine learning [3,1]. Notably, by extending classic suffix-trees we introduce a runtime-efficient data structure to represent human behaviour according to our model, and we develop novel clustering algorithms which employ trails of landmarks in order to calculate similarity between individuals.

Research findings early in the development of our participatory approach, especially in the Urban Tapestries project undertaken in collaboration with Proboscis, an artist-led studio, highlighted its distinct advantages in terms of rapid deployment, adaptability and manageability and elicited considerable interest within the research community. Our work inspired numerous research projects adopting the same methodology, including MobiTOP (Korea), TUCANS (EPSRC-funded), Ubirock Machine (Akademy of Finland) and most notably the NSF-funded Participatory Sensing, as well as our own projects Feral Robots (EPSRC), Snout (Art Council of England) and Sensory Threads (EPSRC). Our subsequent research showed how to combine multiple unreliable signals to construct accurate co-presence networks linking individuals who regularly share the same physical location, and how to merge these with online social networks in order to reconstruct users' social behaviours, resulting in models of cyber-physical social network evolution [1] and leading to the registration of a UK patent (GB2433856).

Founded in 2002, the Pervasive Computing group is led by George Roussos, Professor in Pervasive Computing. His collaborators at Birkbeck include Professor Mark Levene (joined 2001); Research Assistants D. Dially (2005-2007), G. Papamarkos (2006-2008), J. Taylor (2007-2009) and D. Airantzis (2005-2010); and Research Students M. Zoumboulakis (2005-2010), K. Raja (2005-2006), R. Baker (2003-2006) C. Kim (2005-2007) and D. Papadogkonas (2003 – 2008). The group maintains an extensive network of worldwide research collaborations with academic partners (including UCLA, Tokyo, Aalto, Hong Kong, Melbourne, Athens, Rome Tor Vergata, Beijing University of Posts and Telecommunications, UCL and Cambridge), industrial partners (including IBM TJ Watson, Orange, Vodafone, EDF, Lockheed, Balfour Beattie, FEIG, and Smiths Detection) and application stakeholders (including UCLH, Probosics, inmidtown, Brompton Hospital, TfL, and the Zoological Society of London).

3. References to the research

Publications (Birkbeck authors shown in bold)

1. V. Kostakos, E. O'Neill, A. Penn, **G. Roussos** and **D. Papadogkonas**, 2010, Brief encounters: Sensing, modeling and visualizing urban mobility and copresence networks, *ACM Transactions on Computer-Human Interaction (TOCHI)*, 17(1), pp 2:1-2:38. DOI: 10.1145/1721831.1721833
2. Angus, G. Lane, K. Martin, **D. Papadogkonas**, **G. Papamarkos**, **G. Roussos**, S. Thelwall, Z. Sujon and N. West, 2008, Urban Social Tapestries, *IEEE Pervasive Computing*, 7(4), pp. 44-51. DOI: 10.1109/MPRV.2008.84
3. **D. Papadogkonas**, **G. Roussos** and **M. Levene**, 2006, "Analysis, ranking and prediction in pervasive computing trails," *Intelligent Environments*, 2008 IET 4th International Conference on, pp.1-8, 21-22 July 2008. IET Conference Publications. ISSN 978-0-86341-894-5
4. **G. Roussos**, S. Maglavera and A. Marsh, 2005, Enabling Pervasive Computing with Smart Phones, *IEEE Pervasive Computing*, vol. 4, no. 2, pp. 20-27. DOI: 10.1109/MPRV.2005.30
5. **G. Roussos** and T. Moussouri, 2004, Consumer Perceptions of Privacy, Security and Trust in Ubiquitous Commerce, *Personal and Ubiquitous Computing*, vol. 8, pp. 416-429. DOI: 10.1007/s00779-004-0307-6
6. P. Kourouthanassis and **G. Roussos**, 2003, Developing Consumer-Friendly Pervasive Retail Systems, *IEEE Pervasive Computing*, Vol. 2, No 2, pp. 32-39. DOI: 10.1109/MPRV.2003.1203751

Research Grants

1. DeTaLe Project: EPSRC, October 2007-May 2010, £455,000.
2. GeoSciTeach Project: JISC, January 2011-October 2011, £165,000.
3. Visitor Studies with the Experience Recorder: EPSRC Ubicomp Challenge, November 2008-May 2009, £9,000.
4. MyGrocer Mobile Shopping of Electronically Referenced Products: EU FP5 IST (IST-2000-26239), Jan 2001-Aug 2002, 450,000 Euros.
5. Panacea-ITV: EU FP6 IST (IST-2001-33369), Jan 2001-Jan 2004, 650,000 Euros.

4. Details of the impact

Our research in systems architecture, privacy protection and human dynamics has been applied in the development of five systems supporting applications relating to environmental sustainability, healthcare, urban development, transportation, and art:

1. Environmental Sustainability. In response to the call by the Convention on Biological Diversity of the United Nations, the Bat Conservation Society established the Indicator Bats (iBats) biodiversity-monitoring programme (<http://www.ibats.org.uk>). We applied our work in systems architecture to design and develop a smartphone app employed by citizen scientist volunteer groups to collect evidence quantifying bat populations from echolocation signals, subsequently used by the iBats software to infer ecosystem health. According to statistics provided by Apple Market and Google Store, over 7,000 volunteers in 65 countries across the globe have deployed our app on their smartphones. The extended reach of the app has become possible through the application of the techniques described in [4], replacing an assortment of data collection equipment previously employed at a cost of £1,000 per person by the user's smartphone and an ultra-sound microphone costing less than £100. Extensive coverage of what the press has named the Bat Phone has resulted in greater public engagement with the iBats programme. This work was a Medallist for Environmental Project of the Year at the 2011 BCS UK IT Industry awards.

2. Healthcare. Our work on system architecture [5] and human dynamics [1] has been applied to extend the standard Universal Parkinson's Disease Rating Scale (UPDRS) to assess the severity of symptoms of Parkinson's sufferers. Our system employs the advanced inertial sensors, audio, and touchscreen of a smartphone to automatically capture motor performance indicators, which are then made available through secure transmission to the hospital for analysis and safekeeping. By enabling the administration of tests at home, our system reduces the frequency of hospital visits, thus improving the quality of life for sufferers and leading to reduced overall cost of care. Moreover, the assessment of the patient's condition is more precise than using standard UPDRS, which means that the dosage of medication is better controlled. Our system has been validated in a preliminary clinical trial at the National Hospital of Neurology and Neuroscience with a sample of 100 patients and is currently seeking a full clinical study to achieve CE certification for use with the general public.

3. Urban Development. We were commissioned by inmidtown, the business development district of Bloomsbury, Holborn and St. Giles, to apply our research on human dynamics [2,3] in order to develop a participatory sensing system providing evidence of carbon savings as relating to green initiatives being co-ordinated by them. Our system collects location tracking information from a sample of 3,000 volunteers from the 350,000 who work in the district. Our software identifies patterns of users' behaviour, which are employed by inmidtown to inform the redesign of urban flows in the area, specifically aiming to improve the well-being of the working population.

4. Transportation. We have used our models of human dynamics [3] to develop and release a mobile app on Google Play that allows London commuters to optimise their travel expenditure. The app is free and allows any of the 22 million Oyster Card users who choose to download it to save up to 20 per cent of their monthly travel costs. The app has generated significant income for the department through advertising using the Google AdMob system.

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5. Art. Our research in participatory cyber-physical systems [2,4] has been employed in collaboration with Proboscis for the creation of community and performance works of art. These works have been exhibited at several national and international events, attended by over 5,000 participants in total, including Surface Tension (Science Museum, London 2009), Digital Cities (The Building Centre, London 2009), Mobilefest Festival (Sao Paulo, Brazil 2009), Dislocate08 Festival (Yokohama, Japan 2008), and Art and Cartography Exhibition (Wien, Austria 2008).

6. Since 2008, we have engaged with the general public by discussing our research in several trade and general science blogs, magazines and newspapers including Information Week, Financial Times, Daily Mail, New Scientist, Tech Radar, RFID Journal, AIM News, Stern (Germany), and Vima and ERT (Greece). Collectively, these media reach an audience of over 5 million worldwide.

5. Sources to corroborate the impact*Claim 1:*

iBats Project Leader, Bats Conservation Society.

The iBats application for Android <http://goo.gl/b4fgio> and iOS <http://goo.gl/l4QMo> has been downloaded over 7,000 times (July 2013).

Claim 2:

Head, Physiology and Pathophysiology of Human Motor Control, National Hospital for Neurology and Neurosurgery.

The UPDRS <http://goo.gl/nxDlo> application has been released on Google Play in restricted beta release.

Claim 3:

Managing Director and CEO, inmidtown.

The Inmidtown <https://github.com/gkroussos/eco-app> application is currently in early beta release, so has a limited number of downloads at this stage.

Claim 4:

The TfL Fare <http://goo.gl/EqEWr> application has been downloaded over 4,000 times (July 2013) and has generated income recorded by Google's AdMod system.

Claim 5:

Principal, Proboscis.