Institution: Imperial College London

Unit of Assessment: 11- Computer Science and Informatics

Title of case study: Case Study 6 : Body Sensor Networks for Healthcare and Sports (BSN)

1. Summary of the impact (indicative maximum 100 words)

Body Sensor Networks (BSN) research developed novel sensing algorithms and technology suitable for on-body pervasive sensing suitable for healthcare, well-being and sporting applications. The main impact includes:

- Regulatory approval of BSN devices from the Federal Communication Commission (FCC) in 2012 and award of the CE mark in 2009.
- Creation of the BSN technology spin-off company Sensixa in 2007 to manage licencing and commercialisation of the technology.
- Adoption of the technology for training within Team GB in preparation for Winter Olympics 2010, Summer Olympics 2012 in London and other major international sport events.
- Established the use of the technology in a clinical setting.

2. Underpinning research (indicative maximum 500 words)

The concept of Body Sensor Networks (BSN) was introduced to provide "ubiquitous" and "pervasive" monitoring of physical, physiological, and biochemical parameters without activity restriction or behaviour modification [1-2].

Research in the area has been carried out since 2004 at the Centre for Pervasive Sensing led by Professor Yang and his research group in collaboration with Lord Darzi's research group, with initial funding from [i] and [ii]. From the outset, a system level approach to addressing biosensor design was taken with research into materials and biocompatibility, low-power application-specific integrated circuit, wireless communication, autonomic sensing, as well as distributed inferencing and data mining. Major technical hurdles of the BSN technology limiting its adoption are related to difficulties of continuous sensing and monitoring, long-term stability of the sensors and need for low-power operation.

New algorithms amenable to real-time on-node processing and mapping to ultra-low power ASIC (application specific integrated circuit) have been developed. The use of a Bayesian feature selection technique for optimal sensor placement and feature selection for maximising the robustness and information content of the system, whilst minimising the number of sensing channels was successfully combined for the first time [4]. This provides the guiding principle for practical deployment of wearable sensors. To enable sensor miniaturisation and low power operation, a real-time neuro-network framework based on Spatio-Temporal Self-Organising Map (STSOM) has been implemented for mixed-signal ASIC design [5]. The combined use of analogue processing and digital control ensures sophisticated classification algorithms can be implemented on the chip level with very low power consumption. A reflective photoplethysmography sensor was also introduced which enables capturing a user's heart rate without resorting to the use of electrodes [3]. This work set the foundations for BSN research and facilitated the rapid-growth of the field internationally.

The research above resulted in four patents being granted:

1. Patent PCT/GB2007/003861, published as WO2008/047078, filed 11/10/2007, granted 24/4/2008. Pervasive Sensing – a vision-based sensor for smart home application.
2. Patent PCT/GB06/000948, published as WO06/097734, filed 16/3/2005, granted 9/12/2009. Spatial temporal self-organising map – data analysis method which is used partly in the software of the ear sensor.
3. Patent PCT/GB07/000358, published as WO07/088374, filed 02/02/2006 granted 29/1/2009.

Ear sensor for gait analysis.

4. Patent GB 0705033.9: filed 15/03/2007, granted 6/5/2010. Photoplethysmograph heart rate sensing system.

These patents form the basis of an ear-worn activity recognition (e-AR) device. It emulates the sensory function of the ear vestibule for measuring balance, gait, as well as shock-wave transmission through the human skeleton. The innovative design of the device, as well as its intelligent on-node processing, has won the *Medical Futures Translational Research Innovation Award (ENT) 2008* and the *Bluetooth Innovation World Cup 2010* (innovator of the year and winner of the healthcare category, among 270 entries worldwide).

In follow-on research and to support the quest for gold as well as the legacy after the London Olympic Games 2012, the GB sports governing bodies and research councils supported work in applying the sensor to sports training [iii]. One such example was the development of the use of the sensor for swimming. By using the sensor to derive the pitch and roll angles, it was shown to be possible to detect the type of stroke and the wall push-offs. Lap count and split times could be derived. The system represented a non-intrusive, practical deployment of wearable sensors for swim performance monitoring. It was established that for elite swimmers, the development of miniaturised sensors worn on wrists and ankles would provide further insights into the biomotion patterns for more detailed performance analysis [iii].

3. References to the research (indicative maximum of six references)

Publications that directly describe the underpinning research
* References that best indicate quality of underpinning research.

[1] *G.-Z. Yang Ed., Body Sensor Networks, London: Springer-Verlag, 2006 ISBN 978-1-84628-272-0

[2] B. Lo, S. Thiemjarus, R. King and G.-Z. Yang, "Body Sensor Network - A Wireless Sensor Platform for Pervasive Healthcare Monitoring", Adjunct Proceedings of the 3rd International Conference on Pervasive Computing (PERVASIVE 2005), pp.77-80, 2005
Available from http://csis.pace.edu/~marchese/CS396x/L3/p077-080.pdf

[3] *L. Wang, B. Lo and G.-Z. Yang, "Multichannel Reflective PPG Earpiece Sensor with Passive Motion Cancellation", IEEE Transaction on Biomedical Circuits and Systems, 1(4): 235-241, 2007. http://dx.doi.org/10.1109/TBCAS.2007.910900

[4] S. Thiemjarus, B.P.L. Lo, K.V. Laerhoven and G.-Z. Yang, "Feature Selection for Wireless Sensor Networks", the Proceedings of the 1st International Workshop on Wearable and Implantable Body Sensor Networks, April, 2004. Available from
http://vip.doc.ic.ac.uk/benlo/public/Feature_Selection_for_Wireless_Sensor_Networks.pdf

[5] *S. Thiemjarus, B. Lo and G.-Z. Yang, "A Spatio-Temporal Architecture for Context-Aware Sensing", In the IEEE Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks, pp.191-194, 2006. http://dx.doi.org/10.1109/BSN.2006.5

[6] J. Pansiot, B. Lo and G.-Z. Yang, "Swimming Stroke Kinematic Analysis with BSN", In the Proceeding of the International Conference on Body Sensor Networks (BSN 2010), pp.153-158, 2010. http://dx.doi.org/10.1109/BSN.2010.11

Grants that directly funded the underpinning research

[i] BiosensorNet: Autonomic Biosensor Networks for Pervasive Healthcare – EPSRC (EP/C547586/1) £1,403,908, Oct 2005 – Mar 2009. CoI Yang, Darzi & others from Imperial College

[ii] SAPHE (Smart and Aware Pervasive Healthcare Environment) – TSB £1,650,248, Mar 2006 –

Feb 2009. PI Yang

[iii] ESPRIT with Pervasive Sensing (Programme Grant). EPSRC EP/H009744/1, G.-Z. Yang (PI) October 2009 – September 2014, £6,119,249

4. Details of the impact (indicative maximum 750 words)

The spin-out company, Sensixa (http://www.sensixa.com/), was established by Imperial College in 2007 as a company to promote and commercialize the BSN technology described in section 2. It currently holds the IP for the innovative e-AR sensor. The sensor has been developed to allow high volume production via manufacturing facilities in China. The sensor was awarded the CE mark in 2009 and received FCC approval in 2012 which indicate the sensor can be used and sold in both Europe and USA [L].

Coinciding with the London Olympic Games 2012 and as part of the UK's showcase of ICT to the world, BSN technologies developed at Imperial were among the few technologies selected by UKTI during its Life Sciences Technologies and ICT Technology Enabling the Game events [A]. Our work has resulted in innovative training solutions and sports equipment designs to secure competitive advantage for GB athletes. It has also contributed to obtaining an understanding of the biology of athletic performance to gain insights into the human physiological system for improving the health and wellbeing of the population at large. Outcomes of the e-AR sensor and its associated research have led to improvements in elite sport performance monitoring and training for Team GB in the run-up to the London 2012 Olympics, including Rowing, Bobskeleton, Cycling, Sailing, Canoeing and Field Hockey. According to the Head of Sports Science and Research of the British Olympic Association this resulted in "tangible impacts for the preparation of our athletes for Vancouver 2010 and London 2012" [B]. The Head of Research & Innovation at UK Sports state that it has "demonstrated practical and commercial value of BSN through its extensive trials" [C]. The Chief Coach of Women and Lightweights GB Rowing Team states that "providing both athletes and trainers with sport-specific real time feedback allows for understanding of training and race analysis and performance" [D].

The sensor was also used in the rugby union and league where it facilitated national and international teams to maintain their leading ranks. Specifically, work with the Wakefield Trinity Wildcats RL allowed them "to best prepare our playing team for the next Super League game based on the players recovery and then response to an appropriately loaded sessions during the week" [E]. It has been regarded as the "main driving force in the area of endocrinology, behaviour and performance" in sports underpinned by sensing technologies [F]. By using elite athletes as the exemplars, the technology developed has made sport and physical activity more enjoyable and rewarding. It promotes community participation in sport and physical activity and strengthens the feedback loop between exercise and health [G].

The e-AR sensor also has application in the areas of healthcare as it allows one to objectively profile and compare a wide variety of patient outcomes post-operatively, and create a platform for remote patient surveillance and early detection of complications [H]. The e-AR sensor has featured in multiple clinical trials within the Imperial College Healthcare NHS Trust, including three trials that have been recognised and adopted by the NIHR portfolio for further support. Since 2008, over 150 patients and numerous clinical collaborators have been involved in the on-going development of the e-AR sensor. Examples of this includes:

1. In 2008 15 post-operative general surgical patents were remotely monitored at home using the e-AR sensor [I].
2. Between 2010-2011 60 post-operative knee replacement patients had their gait pattern assessed using the e-AR sensor.
3. Between 2009 and 2011 14 knee replacement patients had their peri-operative mobility profiled at home using the e-AR [J].

4. In 2012, 25 patients used the device to supplement the results from ambulatory diagnostic tests.
5. In 2012-2013, 20 patients who had undergone lower limb reconstruction following trauma used the e-AR sensor every 3-months at their follow-up appointments, allowing a system to be developed (Hamlyn Mobility Score) that provides objective recovery information to patients, surgeons and service managers [K].

5. Sources to corroborate the impact (indicative maximum of 10 references.)

[A] B. Lo, L. Atallah, B. Crewther, A.M. Spehar-Deleze, S. Anastasova, A. A. West, P. Conway, C. Cook, S. Drawer, P. Vadgama and G.-Z. Yang. Pervasive sensing for athletic training, Delivering London 2012: ICT Enabling the Games **pp. 53-62**, IET, 2011. Available from http://www.theiet.org/sectors/information-communications/highlights/ict-2012.cfm?type=pdf. Archived here on 22/10/2013

[B] Head of Sports Science and Research, The British Olympic Association confirming details regarding the use of the BSN technology for Olympics Training.

[C] Head of Research & Innovation, UK Sports confirming details regarding the practical and commercial value of the BSN technology for sports training.

[D] Chief Coach, Women and Lightweights, GB Rowing Team confirming the value of the BSN technology for the GB Rowing Team.

[E] Performance Director, Newcastle Knights Rugby Team, Australia, previously Head of Sports Science Support at Wakefield Trinity Wildcat confirming the impact of the BSN technology for rugby sports training.

[F] Sport Performance Coordinator, University Centre Wakefield confirming the impact of the BSN technology for athlete training.

[G] C. J. Cook and B. T. Crewther. Changes in salivary testosterone and subsequent squat performance following the presentation of short video clips. Journal of Hormones and Behaviour, 61:17-22, 2012. http://dx.doi.org/10.1016/j.yhbeh.2011.09.006

[H] O. Aziz, L. Atallah, B. Lo, E. Gray, T. Athanasiou, A. Darzi and G.Z. Yang. Ear-worn Body Sensor Network Device: An Objective Tool for Functional Post-operative Home Recovery Monitoring. Journal of the American Medical Informatics Association (JAMIA), 18:156-159, 2011. http://dx.doi.org/10.1136/jamia.2010.005173

[I] L. Atallah, O. Aziz, E. Gray, B. Lo and G. Z. Yang. An ear-worn sensor for the detection of gait impairment after abdominal surgery. Surgical Innovation, 20:86-94, 2013. http://dx.doi.org/10.1177/1553350612445639

[J] R. M. Kwasnicki, R. Ali, S. J. Jordan et al. An Affordable, Objective Peri-operative Assessment Tool for Knee Arthroplasty. Associations of Surgeons in Training (ASiT) International Surgical Conference, Manchester, UK, 5th-7th April 2013 Oral Prize Session. Int J Surg (2013) http://www.scribd.com/doc/133767897/ASiT-Abstract-Book-2013-Ajb-Jeff-Version-Final-24-March **pg 44** Copy also available on request.

[K] R. M. Kwasnicki, S. Hettiaratchy, J. Simmons, C. Nightingale, G. Z. Yang and A. Darzi. Personal Motion Sensor Directed Rehabilitation After Lower Limb Reconstruction – a New Standard of Care. Plastic & Reconstructive Surgery. 132(4S-1): 55–56, 2013. http://dx.doi.org/10.1097/01.prs.0000435924.58341.98

[L] CE and FCC certificates are available on request.