Institution: Queen's University Belfast

Unit of Assessment: 13

Title of case study: Control technologies for advanced energy efficiency and environmental emission reduction in industrial plants.

1. Summary of the impact

Collaborations funded through EPSRC Interact and RCUK UK-China Science Bridge resulted in QUB's advanced control research having important economic and environmental impact in China, Pakistan, Vietnam. This includes the creation of new core modules for the Shanghai Automation Instrumentation Co (SAIC) SUPMAX Distributed Control System series of products now in use for whole plant monitoring and control to maximise energy efficiency and reduce pollutant emissions. These products have since 2008 increased SAIC's revenue by over $50M p.a. Related networked monitoring technologies have been successfully deployed in Baosteel's hot-rolling production lines and in the Nantong Water Treatment Company that treats 20,000 tonnes of industrial waste water daily.

2. Underpinning research

Key QUB Researchers involved *Li (Lecturer 2002, Senior Lecturer 2007, Reader 2009, Professor 2012) Irwin (Professor 1989) Scanlon (Senior Lecturer 2002, Professor 2008), Lightbody (1989-1997, PhD, Lecturer), Peng (1999-2012, PhD then PDRA, Colandairaj (2003- 2006, PhD), Connally (2003-2006), Niu (2009-2011, PDRA), Du (2009-2010, exchange student, then 2011-2012 PDRA).*

Time period: *1995 to 2012*

Research on modern control techniques in large scale industrial processes and thermal power plants, led by Irwin and Li, has been a UoA major area for many years. This has resulted in important advances ranging from the control of individual units to whole system and networked control. A key aspect has been the use of neural network based methods. These yield new and much less complex models than previously available with proven high effectiveness in control environments that operate over a wide range of system conditions.

Initial research GR/K37161/01 (1995-98) led to new modelling and identification methods and associated algorithms for use in processes where the underlying dynamics are either too complicated to build a white-box model or where process knowledge is either unknown or partially known. Subsequent research GR/S85191/01 (2004-07), investigated the use of neural network methods and resulted in very important advances in a new neural modelling approach based on the use of genetic algorithms for use in non-linear dynamic systems. Here salient non-linear basis functions are extracted, using first principle laws, and used as the basic building blocks to optimally construct appropriate neural network models. These have a simple structure and produce excellent prediction performance and good interpretability [1, 2].

A major challenge is the selection of a small basis function subset from a large candidate pool. However a major breakthrough was made by integrating the forward and backward selection using one integrated framework. Computational requirements significantly reduce by the repetitive application of least squares operations involving matrix inversion. This led to enhanced model performance and greater numerical efficiency [3] as compared with previous orthogonal least squares methods. Application to pollutant emission prediction and control in thermal power plants was demonstrated [4] though collaboration with the British Coal Utilisation Research Association, E.ON UK Power Technology Ltd. Politecnico di Milano and the Shanghai Key Laboratory of Power Station Automation Technology.

Parallel research on whole system control led to other important advances with Multivariate

Statistical Process Control (MSPC) theory being applied to non-linear dynamical process monitoring [5]. This led to new MSPC monitoring software tools that were subsequently developed commercially. An important related challenge is the control of large scale systems where units are geographically distributed and connected via various communication networks. Research in this area EP/F00477X/1 resulted in new wireless network control technologies and a new and verified Simulink co-simulation tool for the IEEE 801.11 protocol. This uses a novel approach to adapt sampling interval based on an 'a priori', static sampling policy and assures control stability - in a mean square sense - by using discrete-time Markov jump linear system theory. In addition, a new inverse Gaussian model for the statistical distribution of network induced delays was created [6].

3. References to the research

The six publications covering/underpinning this research are listed below. These have undergone rigorous peer review and the research funded through the externally peer-reviewed external grants shown. The three highlighted papers* are indicative of the quality underpinning the research.

IEEE Transactions on Automatic Control publishes high-quality papers and technical notes on the theory, design and applications of control engineering. Current Impact factor is 2.11. *Control Engineering Practice*, published by Elsevier is a Journal of IFAC, the International Federation of Automatic Control. It publishes papers which illustrate the direct application of control theory. Current Impact factor 2.03. *IET Control Theory & Applications* is devoted to control systems in the broadest sense, covering new theoretical results and the applications of new and established control methods. Current Impact factor 1.

(1) P. Connally, K. Li, G. W. Irwin. “Integrated Structure Selection and Parameter Optimisation for Eng-genes Neural Models”, Neurocomputing, Vol. 71, No 13-15, 2964-2977, 2008. DOI: 10.1016/j.neucom.2007.06.005 .
(2) Peng, J, Li, K, Thompson, S and Wieringa, P A. "Distribution-based Adaptive Bounding Genetic Algorithm for Continuous Optimisation Problems" (2007). Applied Mathematics and Computation, Vol. 185, pp 1063-1077, 2007. DOI: 10.1016/j.amc.2006.07.022 .
*(3) Li, K, Peng, J and Irwin , G. "A fast nonlinear model identification method" (2005), IEEE Transactions on Automatic Control, vol. 50, no. 8, pp 1211-1216, August 2005. DOI: 10.1109/TAC.2005.852557 . Paper has currently received 113 citations, Scopus.
*(4) K. Li, S. Thompson, J. Peng. "Modelling and prediction of NOx emission in a coal-fired power generation plant" (2004). Control Engineering Practice, Vol. 12, 707-723, 2004, Pergamon. DOI: 10.1016/S0967-0661(03)00171-0. Paper has currently received 44 citations, Scopus.
(5) Hartnett, M., Lightbody, G. and Irwin G.W. "Chemometric techniques in multivariate statistical modelling of process plant" (1996). Analyst, Royal Society of Chemistry, June 1996, Vol. 121, pp. 749-754. DOI: 10.1039/AN99621007496.
*(6) Colandairaj, J, Irwin, G W and Scanlon, W G. "Wireless networked control systems with QoS-based sampling" (2007). IET Control Theory Appl. (formerly published as IEE Proceedings Control Theory & Applications), vol. 1, no. 1, pp 430-438, January 2007. DOI: 10.1049/iet-cta:20050519. Paper has currently received 62 citations, Scopus.

Research Grant funding

UoA Academics George W Irwin (Professor - PI),
UoA Funding EPSRC GR/K37161/01 “ROPA: Performance Enhancement of Complex Industrial Processes by Online Auditing and Prediction”, Mar 1995 to Feb 1998, £106K.

UoA Academics Kang Li (Professor - PI),
UoA Funding EPSRC GR/S85191/01 “Eng-genes: a new genetic modelling approach for real-time operation and control of engineering systems”, May 2004 to August 2007, £124K

UoA Academics George W Irwin (Professor - CI),
UoA Funding EPSRC EP/F00477X/1 “Wireless Interconnectivity and Control of. Active Systems (WICAS)”, Dec 2007 to Nov 2008, £97K.

UoA Academics George W. Irwin (Professor, CI), Kang Li (Professor - CI),

UoA Funding EPSRC EP/C004884/1 "INTERACT: Establishing New Research Links with Chinese Universities and Chinese Academy of Science", April 2005 to May 2006, £18K.

UoA Academics George W. Irwin (Professor, PI), Kang Li (Professor - CI),
UoA Funding RCUK EP/G042594/1 "UK-China Bridge in Sustainable Energy and Built Environment", Sept 2009 to August 2012, £860K.

4. Details of the impact

The research described facilitated major QUB led UK-China collaborations funded through (a) the EPSRC Interact Scheme (2005-2006) and (b) the RCUK UK-China Science Bridge project (2009-2012). These activities created important links between QUB, Shanghai University, Shanghai Automation Instrumentation Co (SAIC) and Baosight and led to the creation of new joint twinned laboratories on energy and automation at both QUB and at the Key Laboratory for Power Station Automation Technology at Shanghai University[1]. QUB's activities have focused on proof-of-concept testing and technology transfer based on the advanced control technologies described, as well as training programmes and thematic workshops, involving UK and Chinese project partners. This led to extensive staff, student and knowledge transfer exchange and further research on the deployment of this new technology in industry.

At SAIC these activities led to the creation of new core modules that have since been incorporated into the company's SUPMAX distributed control system (DCS) series of commercial products, the first of its kind manufactured in China. This has included incorporating QUB's identification and optimisation techniques [1-3] into a networked self-learning control module. This takes the form of an advanced PID self-tuning software package that is part of the Distributed Processing Unit, with this being used for both unit and plant-wide control. In addition, the networked control techniques described [6] have been used to develop a new wireless handset manipulator to improve operation flexibility. A novel Profibus-DP to Ethernet protocol converter has also been developed that significantly improves the communication and control capacity of the SUPMAX products.

SUPMAX DCS has now been used in several major projects for whole plant monitoring and control to maximise energy efficiency and reduce pollutant emissions. In particular, it has been used in the Nantong Waste incineration thermal power generation plant to monitor the whole plant and to control three large circulating fluidised bed waste incinerators. These process 1,500 tonnes of solid waste daily and supply 120 tonnes per hour of steam to nearby companies supplying 200M KWh to China's national grid annually. This plant is now a showcase in China for municipal solid waste incineration/co-generation.

SUPMAX DCS products have also been successfully used in other plants in China as well as in Vietnam, Pakistan and other developing countries where energy efficiency and environmental protection is essential for sustainable development. These showcase projects have led to significant energy savings and environmental protection, with ensuing societal impact. The introduction of these products has also enhanced SAIC's revenues[2] by over US $ 50M p.a. i.e. also has had significant economic impact.

The Multivariate Statistical Process Control MSPC techniques [5] and the wired/wireless networked monitoring and control systems created [6] have also been developed, successfully tested and deployed in the hot-rolling production lines of the Baosteel Group. These have been used for condition monitoring, fault-diagnosis, and information management[3], as well as in the Nantong Water Treatment Co. which treats 20,000 tonnes of industrial waste water daily for the Rugao industrial development zone. The Zhejiang Ninghai and Shanghai Caohejing power stations have also benefitted from the UoA's technology [1-4] using the technology to control, flow rate, pressure and temperature in hydrogen-cooled oil pipeline pressure systems as well as in a 1000MW pulveriser system. Again this has resulted in significant improvements in energy efficiency and control performance.

This impact has led in 2009 to the award of second prize for "Science and Technology Progress" at

the Shanghai Government's annual Science and Technology Awards Conference and in 2010 to the award of the "Creation Prize" at China's International Industry Fair in 2010, organised by China's National Development and Reform Commission and several Chinese government ministries.

Tackling climate change and maintaining energy security are twin challenges facing both developed and developing countries. China is now the second largest consumer of primary energy and the world's top country for CO2 emissions. The research undertaken is therefore having an important impact in helping to address these societal and environmental issues.

Note SAIC, (part of the Shanghai Electric Group), is the world's largest manufacturer of steam turbines, http://www.shanghai-electric.com/en/Pages/default.aspx). Baosight, (part of the Baosteel Group) is the world's second-largest steel producer measured by crude steel output (www.baosteel.com/group_en/).

5. Sources to corroborate the impact

[1]Leader of the UK-China Science Bridge Joint Lab on Energy and Automation
Shanghai University.

[2]Chief Engineer SUPMAX product development, applications and sales:
Shanghai Automation Instrumentation Co. Ltd.

[3]Chief engineer Central Technology of Baosteel Detection Co. Ltd
Baosteel Co., Ltd.

RCUK funded UK-China Science Bridge project at Queen's University Belfast
http://www.qub.ac.uk/sites/sciencebridge/

UK-China Science Bridge joint laboratory on power and automation
http://202.121.199.239/fcms/Html/englishversion/

SUPMAX distributed networked monitoring and control systems
(http://www.zygfw.com/prolist.asp?id=264&nid=418)

Chinese language sites:
Second prize for advancing science and technology awarded by the Shanghai Government in 2009 (The key technologies for networked measurement and control system and power plant automation) http://www.shjlb.org.cn/newshow_k.aspx?id=142

Creation prize in the China International Industry Fair in 2010
"Measurement and Control System based on hybrid networks towards the Internet of things oriented applications"
http://210.13.115.29/gbh/fun/winner-his.action?years=2010