Institution: University of Huddersfield
Unit of Assessment: 11 Computer Science and Informatic
Title of case study: Engineering Knowledge for Autonomous and Intelligent Systems

1. Summary of the impact

University of Huddersfield research into knowledge engineering, domain modelling and machine learning has raised professional, industry and policymaker awareness of novel ways of designing more efficient, cost-effective and sustainable management networks. This is particularly the case in the field of transportation, where recognition of such techniques has significantly increased among stakeholders throughout the UK and across Europe. The research has been credited with informing a "step-change in thinking" and is now central to the £16m EPSRC Autonomous and Intelligent Systems Programme, which has attracted more than £4m in financial and in-kind support from hi-tech industries.

2. Underpinning research

The development of autonomous systems will, according to UK Chancellor George Osborne, "revolutionise our economy and society over the next 20 years". Since joining the University of Huddersfield from The City University, London, in 1993, Professor Thomas Leo (Lee) McCluskey, Chair of Software Technology, has been developing ways of knowledge engineering for intelligent systems in order to embed them with autonomy. *Execution Autonomy* is where a system carries out a given process automatically in dynamic and unpredictable environments, making decisions without human intervention when necessary. *Design Autonomy* is where a system is given goals, and itself creates the process to be carried out within an external environment to achieve those goals. McCluskey's work centres on harnessing artificial intelligence (AI) technologies to manifest design autonomy, in particular autonomic properties such as self-management and adaptation, into systems. His application focus has been on systems which underlie, control and optimise transport networks, for the benefit of improving efficiency, reducing human error and cutting costs.

From 1992-1994, (first at City University, then at Huddersfield) McCluskey was PI of a series of contract research grants with UK National Air Traffic Services Ltd (now NATS Holdings Ltd). This research explored the use of rigorous methods in the construction of models for domains, resulting in the production of a logical model of air traffic criteria for safety-critical oceanic operations in the North Atlantic. Including flight information, this model consisted of several thousand axioms encoded in many-sorted logic [ref 1]. The model captured the knowledge underlying decision support systems for air traffic controllers in order to be used in the development of replacement software to perform Conflict Prediction (that is, predicting whether or not planned aircraft flight profiles obey separation standards) for the Oceanic region. This led to the responsive mode project IMPRESS, carried out at Huddersfield between 1996-1998 with McCluskey as PI, funded by the EPSRC, the Ministry of Defence and with in-kind support from the UK NATS Ltd [ref 7]. The research project's key result [ref 3] was a method to apply machine learning techniques to *self-adapt* the large logical model of air traffic criteria referenced in [ref 1]. The method, the first of its kind to be applied to a large, logical model representing knowledge of a real application, enables a system to find bugs in its domain model and update the model to fix the bugs, hence performing self-repair / self-maintenance, which are seen as important properties of autonomic systems.

At the same time this fieldwork inspired McCluskey to create an object-centred language and method for encoding domain models for *automated planning and scheduling* (APS), an area which can enable design autonomy, and the machine learning tools that support it [ref 2]. The key insights of this work – to do with the importance of knowledge engineering in APS – focused the energies of a section of the APS community on this issue in order to offer modellers a more engineering-oriented domain model language than previously used in planning research. This led directly to PLANFORM, a collaborative EPSRC-funded project [ref 8], starting in 1999, of which McCluskey was PI at Huddersfield, with the Universities of Salford (PI: Ruth Aylett) and Durham (PIs: Maria Fox and Derek Long). Huddersfield's contribution was as lead partner and to perform research in the knowledge engineering aspects of APS. To help in the development and dissemination of this underpinning research, McCluskey led the knowledge engineering unit of the

EU-funded framework IV network of excellence PLANET (2001-2004), which resulted in an APS roadmap containing a section on knowledge engineering for APS edited by McCluskey [ref 4]. Huddersfield also developed its GIPO tool [ref 5], an experimental environment for exploring the use of knowledge engineering tools in planning systems, which won first prize for best tools platform at the International Competition on Knowledge Engineering for Planning and Scheduling (ICKEPS) in Monterey, California, in 2005. Utilising GIPO's domain representation, further work on learning planning domain models followed [ref 6].

In sum, McCluskey's research provided insights into how to engineer domain models for automated planning [refs 2, 4, 5, 8], how to encode transport domain models [refs 1, 7] and how to utilise machine learning in engineering domain models [refs 2, 3, 6, 7].

Role of other named researchers in research and publications [ref 1 – 6]:

McCluskey carried out all the underpinning research claimed in association with his research fellows and research assistants, and lecturer colleagues at Huddersfiled, in [refs 1, 2, 3, 5, 6] as follows: Naik, Taylor, Jones, were research staff responsible to Prof McCluskey at City University up to when he left in August 1993; Porteous, Cresswell and West were research staff responsible to Prof McCluskey at Huddersfield; Simpson and Kitchin were lecturing staff at University of Huddersfield. Other named researchers in [ref 4] were leaders of other Technical Co-ordination Units from universities throughout Europe within the Planet Network of Excellence (except Biundo, who was Network Chair).

3. References to the research

Outputs:

[1] T.L.McCluskey, J.M.Porteous, Y. Naik, C.N.Taylor and S.V.Jones (1995). A Requirements Capture Method and its use in an Air Traffic Control Application. *Journal of Software - Practice and Experience*, VOL.25(1), 45-71. DOI: 10.1002/spe.4380250104.
[2] T.L.McCluskey and J.M.Porteous, (1997) Engineering and compiling planning domain models to promote validity and efficiency *Artificial Intelligence* , 95 (1), pp. 1-65. ISSN 0004-3702
[3] T.L.McCluskey and M.M.West (2001) The automated refinement of a requirements domain theory *Journal of Automated Software Engineering* , 8 (2), (Special Issue on Inductive Programming), Kluwer Academic Publishers, pp. 195-218. ISSN 1573-7535.
[4] Biundo, Susanne, Aylett, Ruth, Beetz, Michael, Borrajo, Daniel, Cesta, Amedeo, Grant, Tim, McCluskey, Lee, Milani, Alfredo and Verfaille, Gerard (2003) Technological roadmap on AI planning and scheduling. Project Report. European Community under the Information Society Technology Programme, Ulm, Germany.
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.77.7776&rep=rep1&type=pdf
[5] R.M.Simpson, D.E.Kitchin, and T.L.McCluskey, (2007) Planning domain definition using GIPO. *Knowledge Engineering Review*, 22 (2). pp. 117-134. ISSN 0269-8889.
[6] S.N.Cresswell, T.L.McCluskey and M.M.West, (2009) Acquisition of Object-Centred Domain Models from Planning Examples. *In: Proceedings of the Nineteenth International Conference on Automated Planning and Scheduling (ICAPS 2009)*. Menlo Park, California, USA: AAAI Press. pp. 338-341. ISBN 9781577354079

Grants:

[7] 1996-98 GR/K73152: "IMPRESS - Improving the quality of formal requirements specifications using machine learning techniques". Principal Investigator: T.L.McCluskey. EPSRC responsive mode award with funds of c.£155,000 plus c.£100,000 in kind support from NATS Ltd.
[8] 1999-02 GR/M67421: "PLANFORM - An open environment for building AI planners" Principal investigator: T.L.McCluskey. Collaborative EPSRC responsive mode award with funds of c.£290,000 split equally between the 3 Universities of Huddersfield, Salford and Durham, plus in-kind support from UK NATS Ltd, and CogSys Ltd. http://planform.hud.ac.uk/

Evidence of quality of publications:

[refs 1,2,3,5] are all significant journal papers in well established journals, and the work reported builds on the author's publications in refereed conferences such as ICTAI 96,98,00, ECP-97, and ASE-99. [ref 4] is a substantial roadmap, and [ref 6] is a paper in a top rated conference, ICAPS.

4. Details of the impact

University of Huddersfield research has significantly raised awareness of new ways of designing more efficient, cost-effective and sustainable management networks using knowledge engineering, automated planning, domain modelling and machine learning techniques. It is now playing a leading role in the £16m EPSRC Autonomous and Intelligent Systems Programme, which has attracted more than £4m in financial and in-kind support from hi-tech industries.

McCluskey's work has been central to galvanising a shift towards the adoption of design autonomy and autonomic systems, in particular the implementation of properties of self-management, self-maintenance and adaptation within transport systems. As well as via the dissemination of scholarly work, this has been achieved through involvement with technology transfer events, joint industry-university projects and professional groups. Examples in the area of road transport have included 'Artificially Intelligent *Intelligent Transport Systems*?', a talk at Portsmouth for more than 50 road transport consultants on the value of intelligent systems in road transport systems (November 2009) [ref A]; 'Intelligent ITS? From component intelligence to self-awareness' a talk invited by the Technology Strategy Board at Innovate '11: Connect for Growth under the seminar 'Mobility with Intelligence in 2015', attended by approximately 70 transport professionals (October 2011) [ref C]; and an article on domain modelling for Air Traffic Technology International, a professional publication aimed at air traffic experts (2009) [ref B].

The Portsmouth conference in particular was pivotal in a move towards wider recognition of the value of truly intelligent transport systems, as demonstrated by feedback from delegates. The Technology Strategy Board's Innovation Platform Leader for ITTS remarked that the event signalled a "move away from the usual non-productive debates" [ref A]. It led to the formation of the iMFV (intelligent mobility: future vision) collaboration (http://www.hud.ac.uk/imfv/), with McCluskey as one of the founding members. iMFV's members and associates are transport consultants and professionals who work with McCluskey to "influence change in society's attitudes to mobility as part of a wider review of transport in society" and to "change the behaviour (or the way of thinking) not only of end users but technology providers, planners and policymakers" [ref D]. The Director of SG Transport Innovation Ltd, a founder member of iMFV, has confirmed that McCluskey's work has "influenced thinking within the transport arena" and "raised awareness of the potential AI holds for the management of complex urban road networks" [ref E].

The significance of McCluskey's research was further recognised in 2011 with the award by COST, an intergovernmental framework for European Cooperation in Science and Technology, of a major project, Towards Autonomic Road Transport Systems (ARTS), within its Transport and Urban Development area [ref G]. As Action Chair for ARTS, McCluskey leads a consortium of members from universities, consultancies, transport authorities and industry from 24 countries throughout Europe, aimed at advancing the state of the art in engineering transport technologies in order to address problems in road transportation networks such as traffic overload and environmental consequence. This is resulting in widespread dissemination of leading-edge research in computer science to the road transport community through seminars, co-located workshops, academic-practitioner meetings, training schools and cross-national study visits. Recent examples include a meeting with Newcastle and Gateshead City Council in April 2013 to discuss delivering cost savings and improving network efficiency through the use of autonomic transport systems. A training school organised by COST ARTS in Paris in May 2013 attracted over 50 transport-related early career participants and featured McCluskey as a speaker [ref I]. The Managing Director of transport consultancy KAM Futures has reported that the ideas and networking opportunities resulting from the ARTS network have led to his company's involvement in nine project proposals "with combined value of over £2.5m, with currently a greater than 50% success rate" [ref F],

adding: “The ideas and techniques emanating from McCluskey’s research... are currently informing a step-change in thinking.” The Director of SG Transport Innovation Ltd has observed: “The impact of [McCluskey’s] research is being felt within the UK and also European-wide through the COST Action.” [ref E]

In May 2012 Minister of State for Universities and Science David Willetts, announced £16m in funding from government and industry for a series of high-profile projects in the Autonomous and Intelligent Systems Programme, aimed at developing intelligent autonomous systems deemed vital to the future competitiveness of UK companies in sectors including advanced manufacturing, energy, transport, healthcare and defence. The underpinning research reported in [refs 1-6] led to McCluskey and Professor Austin Tate, of the University of Edinburgh, winning one of the first tranche projects, Machine Learning and Adaptation of Domain Models to Support Real-Time Planning in Autonomous Systems, which is being carried out at Huddersfield and Edinburgh (website: http://www.aiai.ed.ac.uk/project/hedlamp/, EPSRC awards £366,420 and £348,426 respectively, EP/J011991/1 and EP/J011800/1). McCluskey is leading this EPSRC project, known as HedLamp for short, to develop the capacity for robotic machines to learn and adapt knowledge in order to make their own plans and decisions. Major industrial partners such as BAE Systems, Schlumberger, National Nuclear Laboratory, Sellafield Ltd, Network Rail, SCISYS, DSTL and the UK Space Agency are providing over £4m in financial support and technical expertise. HedLamp is already influencing the practice of leading multi-national oilfield services provider Schlumberger, where, as confirmed by one of the company’s Program Managers, it has encouraged “new ways of thinking about encoding information, process and control” [ref J]. Work resulting from HedLamp was recently presented to Schlumberger’s CEO and is considered “an important part of the overall effort in automation in oilfields” [ref J].

5. Sources to corroborate the impact

[A] Intelligent Transport Systems: Future Vision, 5th November 2009, University of Portsmouth, Langstone Conference Centre, details on http://www.hud.ac.uk/imfv/eventpresentationsandoutcomes/
[B] McCluskey, T. L. and West, M. (2009) ‘Ontological Engineering and ATC’ *Air Traffic Technology International 2009*, pp. 63-65. ISSN 1366-7041
[C] INNOVATE ’11: Speaker and panel member on “Travel and Transport Mobility with Intelligence in 2015” Seminar. http://webarchive.nationalarchives.gov.uk/20130221185318/https://connect.innovateuk.org/web/innovate-11/overview
[D] Testimony of the Leader of iMFV (with University)
[E] Testimony of Director of SG Transport Innovation Ltd (with University)
[F] Testimony of Managing Director of KAM Futures (with University)
[G] http://www.cost.eu/domains_actions/tud/Actions/TU1102/
[H] COST ARTS Working Group Report: Newcastle, April 2013 (with University)
[I] COST ARTS Summer School http://helios.hud.ac.uk/cost/summerschool.php
[J] Testimony of the “Program Manager: Monitoring and Control”, Schlumberger Gould Research (with University)