Institution: University of Essex

Unit of Assessment: 11 – Computer Science and Informatics

Title of case study: Type-2 Fuzzy Logic: Managing uncertainty and imprecision in telecoms and finance

1. Summary of the impact

Professor Hani Hagras' research into type-2 Fuzzy Logic Controllers (FLCs) underpins novel control systems which avoid the drawbacks and shortcomings of the type-1 FLCs used in numerous real world applications. Type-2 FLCs, developed at Essex, enable challenging applications to be realised and managed with better accuracy and robustness. Such applications include:

- Telecommunications:
  - British Telecom employ type-2 FLCs for capacity planning, improving the efficiency of their workforce deployment
- Finance:
  - LogicalGlue Ltd applied type-2 FLCs to develop a group decision-making system which outperforms existing commercial counterparts
  - Discovery Investing Scoreboard Inc. use type-2 FLCs to identify early stage investment opportunities

2. Underpinning research

Since the invention of fuzzy logic more than four decades ago, great progress has been achieved using type-1 FLCs, which are applied to a huge number of real world applications, including domestic appliances and industrial automation. However, it became apparent that type-1 FLCs cannot fully handle the numerous uncertainties encountered in real world environments, as type-1 FLCs employ 'crisp' type-1 fuzzy sets. As a result, since 2000 there has been renewed interest in systems which make use of type-2 fuzzy logic (based on the work of various researchers in the USA (such as Professor Jerry Mendel) and Europe (such as Professor Robert John)). This has stemmed from the fact that type-2 fuzzy sets are three-dimensional and have higher degrees of freedom, meaning that they can avoid the drawbacks of type-1 FLCs. However, before 2002, type-2 fuzzy logic systems (FLSs) were deemed too computationally expensive to be applied to real world control applications.

In 2002, Hagras (then as Lecturer) presented real-time type-2 FLCs capable of handling the high levels of uncertainty experienced in real world applications. Since 2002, as Senior Lecturer and Professor, his subsequent research has led to the realisation of theoretical and practical innovations that can avoid the computational overheads previously associated with type-2 FLSs, allowing type-2 FLCs to operate in real-time. His research has involved the introduction of hierarchical type-2 FLCs (Hagras, 2004), hardware, including type-2 fuzzy co-processors (Wagner and Hagras, 2010), as well as the development of new theoretical algorithms to avoid computational overhead (Lynch et al., 2006). An additional focus has been the development of learning techniques to enable the optimal design of type-2 FLCs, leading to novel neuro and genetic type-2 FLCs (Hagras et al., 2007).

Finally, Hagras' research has also generated real-time general type-2 FLCs, thus unleashing the full power of type-2 FLCs. A key result of these efforts was the realisation of the first type-2 FLC for industrial use, which was applied to the speed control of marine engines manufactured by MAN B&W Ltd (Lynch et al., 2006). Building on this achievement, Hagras and his students continued their efforts towards effective realisation of many of the first real world type-2 FLC applications

(Lynch et al., 2006; Hagras et al., 2007; Jammeh et al., 2009; Lee et al., 2010). These efforts have resulted in the more universal acceptance of type-2 FLCs, the benefits that they have to offer, and their subsequent exploitation in a global and diverse range of sectors and applications.

3. References to the research

Hagras, H. (2004) A hierarchical type-2 fuzzy logic control architecture for autonomous mobile robots, *IEEE Transactions on Fuzzy Systems,* 12, 524-539. (469 citations – November 2013) DOI:10.1109/TFUZZ.2004.832538

This paper was awarded, by IEEE Computational Intelligence Society (CIS), the 2004 IEEE Transactions on Fuzzy Systems Outstanding Paper Award. The award citation states: "The paper has presented major original theoretical advances to the field of type-2 fuzzy systems. The paper has also presented ground breaking results which showed for the first time how the type-2 FLC can handle the uncertainties in changing and dynamic unstructured environments. This paper will have a major impact on advancing the fuzzy control research and its application".

Lynch, C., H. Hagras and V. Callaghan (2006) Using uncertainty bounds in the design of an embedded real-time type-2 neuro-fuzzy speed controller for marine diesel engines, *Proceedings of IEEE International Conference on Fuzzy Systems, Vancouver, Canada,* pp.1446-1453. (62 citations – November 2013) DOI:10.1109/FUZZY.2006.1681899

Hagras, H., F. Doctor, A. Lopez and V. Callaghan (2007) An incremental adaptive life long learning approach for type-2 fuzzy embedded agents in ambient intelligent environments, *IEEE Transactions on Fuzzy Systems*, 15, 41-55. (77 citations – November 2013) DOI:10.1109/TFUZZ.2006.889758

Jammeh, E., M. Fleury, C. Wagner, H. Hagras and M. Ghanbari (2009) Interval type-2 fuzzy logic congestion control for video streaming across IP networks, *IEEE Transactions on Fuzzy Systems*, 17, 1123-1142. (58 citations – November 2013) DOI:10.1109/TFUZZ.2009.2023325

Lee, C., M. Wang and H. Hagras (2010) A type-2 fuzzy ontology and its application to personal diabetic diet recommendation, *IEEE Transactions on Fuzzy Systems*, 18, 374-395. (77 citations – November 2013) DOI:10.1109/TFUZZ.2010.2042454

Wagner, C. and H. Hagras (2010) Towards general type-2 fuzzy logic systems based on zSlices, *IEEE Transactions on Fuzzy Systems*, 18, 637-660. (105 citations – November 2013) DOI:10.1109/TFUZZ.2010.2045386

This paper was awarded, by IEEE Computational Intelligence Society (CIS), the 2010 IEEE Transactions on Fuzzy Systems Outstanding Paper Award. The award citation states: "This seminal paper allowed breakthroughs to the theory and applications of type-2 FLCs where the paper presented a complete "modern" approach to design and realize general type-2 FLCs based on zSlices type-2 fuzzy sets".

Research funding:

European Commission:

Callaghan and Hagras, *eGadgets*, Jan '01 – Jan '04, £237,000

Callaghan, Colley and Hagras, *SOCIAL: Self-Organised Societies of Connectionist Intelligent Agents capable of Learning*, Jan '03 – May '06, £286,761

Hagras, Colley, Fowler and Callaghan, *ATRACO: Adaptive and Trusted Ambient Technologies*, Jan '08 – Jun '11, £542,782

Other sponsors have included the ESRC, TSB (four projects totalling ~£800k), The Taiwan National Science Council (three projects totalling ~£150k) as well as sponsors from the private sector, including BT (five projects totalling ~£260k) and MAN B&W (~£56k).

4. Details of the impact

Many 'real world' processes, both industrial and domestic, are affected by high levels of uncertainty and imprecision. Fuzzy logic systems (FLSs) laid the basis for a successful method to model vagueness, uncertainty and imprecision. Type-2 FLCs, capable of real-time operation and which can overcome the drawbacks of type-1 FLCs, developed and presented by Hagras and his students, have enabled applications that were not previously possible. The underpinning research sparked a strong interest from industry where there is a need to develop intelligent systems which can handle high uncertainty levels and deliver responses which avoid the drawbacks of existing systems. As a result of the work of Hagras and his students, type-2 FLCs have directly underpinned the realisation of impact in a number of real world contexts.

Telecommunications:

British Telecom (BT): BT employs a large mobile workforce, in which engineers cover particular geographic areas and are assigned jobs in response to customer needs. Given the size of this workforce and the complexities of its deployment, ensuring the most efficient use of skills and resources is extremely important. It was recognised that systems developed at Essex would be ideally suited for handling the level of uncertainty associated with this task and thus, under a research contract beginning in 2010, the project *'Distributed and Fuzzy Resource Planning'* was established [see corroborating source 1].

The project used type-2 FLCs, developed at Essex, to accommodate the inherent uncertainties and imprecision associated with workforce capacity planning; for example, in intelligently deploying engineers to cover overlaps in coverage encountered at multiple adjoining geographic areas. Fuzzy boundaries and shifts were created, and engineers were matched to multiple areas, to enable optimum and dynamic allocation of skills and resources. In 2011, a newly developed system, based on the insight of this research, demonstrated a considerable saving of engineers' time. This improved efficiency has resulted in a greater throughput of job completion for customers. In a letter of support, the Head of Resource Management Technologies Research at BT acknowledges the importance and usefulness of this research. In recognition of its efficacy, BT intends to apply the system for managing its workforce deployment throughout the UK [2].

Financial applications:

LogicalGlue Ltd: In 2006, a Knowledge Transfer Partnership was undertaken between the University of Essex and Sanctuary Personnel Ltd, which resulted in the formation of LogicalGlue Ltd in 2009. A type-2 FLC was deployed by LogicalGlue to develop a group decision-making system for various domains. Within the financial domain, the fuzzy system has been used for credit scoring and has consistently outperformed existing commercial counterparts. During independent technical trials with a leading credit rating agency, LogicalGlue's website reports how the company's system demonstrated an 11% uplift in spotting defaults in credit card data when compared to leading statistical regression systems [3]. In a letter of support, LogicalGlue's CEO goes on to explain: "As well as the capability of these implementations to handle uncertainty, their 'white-box' transparency also meant that the reasoning behind given decisions could be understood; it enabled the system to provide an explanation of its operation, in a user-friendly, easy to interpret and language-based system" [4].

This work was awarded the 2009 Lord Stafford Award for Achievement in Innovation for East of England. The award citation stated: "…the result is a product that is not only benefiting IPFour [the parent company of Sanctuary Personnel Ltd] but could also have a much further reach" [5]. In 2011 the project was also named the best KTP in London and the East region [6] and listed as a finalist in the TSB's 'Best of the Best' awards [7, see page 6], at a time when approximately 1000 other projects were in progress. Two further KTPs (entitled '*Developing Intelligent Data Integration and Visualisation Tools*' (January 2010 – December 2013, £211,266) and '*Developing Intelligent Adaptive Systems for Process Control and Production Optimisation in the Oil Refining Industries*' (August 2010 – August 2013, £197,266)) have been awarded to the company and the University, to continue knowledge transfer projects.

Discovery Investing Scoreboard Inc.: Since 2010, USA-based Discovery Investing Scoreboard Inc. has used Hagras' research to develop a free online service for evaluating the investment potential of companies. It was recognised, in particular, that micro- or small-capitalisation companies are often not established enough to be able to demonstrate the necessary data, references or proven assets that might be required to measure suitability for investment via traditional methods of investment analysis. However, in many cases, it is these small or early stage companies in which many of the most prudent investments can be made, before they have the opportunity to fully exploit their potential for growth. The type-2 FLSs employed by Discovery Investing enable handling of encountered linguistic uncertainties and can be used to produce a score of a company's 'discovery potential', associated with a given level of imprecision. The company's CEO believes that the system is the first commercial product to use interval type-2 fuzzy logic in a language-based computing implementation for application to the digital economy. In a letter of support he explains how "The system has been in use for one and one-half years and is having a deep impact for evaluating businesses in the USA and in other emerging and existing companies all over the world. I am delighted to acknowledge the value of the insight which Professor Hagras' research provided in this instance" [8].

5. Sources to corroborate the impact [All sources saved on file with HEI, available on request]

[1] Agreement between British Telecommunications plc. and University of Essex (2010), relating to "Distributed and Fuzzy Resource Planning"

[2] Head of Resource Management Technologies Research, BT

[3] LogicalGlue Ltd *About Us. Award-Winning Advanced Business Analytics Software* [online] Available from: http://www.logicalglue.com/about-us/ [Accessed 9 July 2013]

[4] CEO, LogicalGlue Ltd

[5] Praxis Unico, 2009. *Leading university research wins prestigious award* [online] Available from: http://www.praxisunico.org.uk/news/member-detail.asp?ItemID=234 [Accessed 9 July 2013]

[6] Email from the Head of Knowledge Exchange, Technology Strategy Board, sent to the HEI in August 2011

[7] Technology Strategy Board, 2011. *Best of the Best. KTP Awards 2011* [pdf] Available from: http://www.ktponline.org.uk/assets/2011/special/2011AwardsBestOfBest.pdf [Accessed 9 July 2013]

[8] CEO, Discovery Investing Scoreboard Inc.