International Journal of Uncertainty,
Fuzziness and Knowledge-Based Systems
Vol. 19, No. 3 (2011) 417–422

DOI: 10.1142/S0218488511007064

RECENT ADVANCES IN FUZZY QUALITATIVE REASONING

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Received 27 March 2011
Revised 28 March 2011

1. Fuzzy Qualitative Reasoning Revisited

Fuzzy qualitative reasoning (FQR) is a form of approximate reasoning that can be defined loosely as the fusion of Fuzzy Reasoning (FR) with Qualitative Reasoning (QR). Both these research areas have as one of their goals the construction of computational reasoning tools that can predict and explain the behaviour of, often dynamic, systems whose analytic relations are incompletely specified. Whereas pure FR utilizes black box models, QR utilizes explicit structural models. And whereas pure QR operates with symbolic 'quantities', FR explicitly reasons with fuzzy intervals of varying precision that are supported directly by the real number line.

Fuzzy reasoning has evolved significantly and attracted a great deal of attention and exploitation from the industrial and research communities in the forty or so years since its inception. It is good at facilitating communication with sensing and control level subsystems and it utilises powerful reasoning strategies through conditional statements so as to easily handle mathematical and engineering systems in model free manner. Fuzzy reasoning also provides a means of handling uncertainty in a natural way making it robust in significantly noisy environments. However, the fact that its knowledge is primarily shallow, and the questions over the computational overhead associated with handling grades of membership of discrete fuzzy sets must be taken into account if deeper reasoning is to be carried out.

On the other hand, qualitative and model-based reasoning has been successfully deployed in many applications such as autonomous spacecraft support, biomedicine, and qualitative systems identification. It has the advantage of operating at the conceptual modelling level, reasoning symbolically with models that retain the mathematical structures of the problem rather than the input/output representation of rule bases (fuzzy or otherwise). These models are incomplete in the sense that, being symbolic, they do not contain or require exact parameter information about the constitutive relations of the model in order to operate. Qualitative reasoning can make use of multiple ontologies, explicitly represent causality, enable the construction of more sophisticated models from simpler constituents by means of compositional modelling, and infer the global behaviour of a system from a description of its structure.

The fusion that is FQR captures the strengths of both these approaches: the integration of fuzzy set logic with structured qualitative models enables, on the one hand, the envisionment and/or simulation of system behaviours at higher levels of precision, and, on the other hand, the embedding of structural knowledge into fuzzy identifiers that results in an improved interpretability and robustness of nonlinear system identification from input-output data. In consequence, FQR enables the successful performance of reasoning tasks, at the appropriate levels in application domains that are particularly problematic from the modelling point of view for either on its own.

The history of FQR development can be broadly represented by the tools, techniques and method, (such as QSIM, FuSim or Morven) developed to solve real world problems areas as diverse as robotics, computer vision, process engineering and biology. Perhaps the earliest approach tried was that of Dubois and Prade[8] who combined fuzzy reasoning with Forbus' Qualitative Process Engine. This was closely followed by the work of Shen and Leitch[22] who took a similar general approach but used Qualitative Simulation (QSIM) as the template for development. QSIM was developed by Kuipers,[16] and is a constraint based QR package utilising qualitative differential equations (QDEs) – which are abstractions of ordinary differential equations – to specify the constraints. FuSim,[22] represents the values of variables as parameterised four-tuple fuzzy numbers which constitute the fuzzy quantity spaces, in contrast to the symbolic values utilised in QSIM. This allows the model to be analysed more precisely over time whilst retaining the essential features of QR. One major limitation of QSIM and FuSim was the use of only one derivative per variable. Morven,[7] formerly known as Mycroft, is a qualitative reasoning framework built on ideas developed in FuSim and adding several novel features. For example, the introduction of fuzzy vector envisionment that provides variable precision pictures of the qualitatively distinct behaviours of a dynamic system, and the ability to perform non-constructive numerical simulation. Some of the latest developments in this strand of research are included in this issue.

In robotics research, Blackwell did pioneering work on spatial reasoning on robots.[1] However, while some effort has been expended on developing qualitative kinematic models, the results have been limited.[10,11,21] A basic requirement for progressing in this domain was the development of a qualitative version of the trigonometric rules. Buckley and Eslami[3] proposed the definition of fuzzy trigonometry from the fuzzy perspective without consideration of the geometric meaning of trigonometry. For this purpose, Liu *et al.* attempted two completely different approaches[17,18,20] based on fuzzy qualitative trigonometry.[19] The original version of this method was not implemented for spatial robots due to its computational cost and complex spatial relation; though it was applied to planar robots. However, conventional robotics had been extended with the fuzzy qualitative trigonometry; not only did the implementation demonstrate the feasibility for spatial robots but also it shows the promise of potential applications in intelligent robotics.[18]

In the field of computer vision it is difficult to carry out real-time processing and achieve algorithmic scalability, because of the data intensity associated with digital video images. Chan and Liu have developed a number of FQR tools[4,5] that can outperform existing solutions in the sense of flexibly handling the trade-off between human motion precision and its computation efficiency. They facilitate the creation of a human motion database and are the basis for a unified human motion recognition system. In addition they have taken steps towards overcoming the problems associated with the semantic gap that exists between the video data (signal) and the human observer (symbol).

In contrast to the above another interesting approach to combining FR and QR focused on the bio-medical domain is that of Ironi *et. al.*. They utilise a QSIM model to identify the qualitative behaviours of the system of interest and from this identify a suitable set of rules from which they parameterise a fuzzy system. This is then utilised to make predictions under a variety of medically relevant conditions.[12] This work has been under continuous development and the latest research in this line is also included in this special issue.

2. Contents of the Special Issue

The papers contained in this issue build on the work already done in the field and address a number of outstanding issues. Seven papers have been selected for inclusion which has been divided into the two categories of theoretical developments in FQR and the application of FQR.

The first category consists of four papers that present new FQR research findings.[6,9,13,14] Guglielmann and Ironi, building on their previous work, present a divide-and-conquer strategy which makes qualitative simulation tractable and the derived behavioural description comprehensible and exhaustive and consequently usable to perform system identification. Having in mind a key cause of intractable qualitative simulation, it decomposes a knowledge base of complete qualitative models into compartmental model fragments containing all unrelated events, but without losing the entire range of possible dynamical distinctions. The method is evaluated in a dynamical system from the biomedical domain with an emphasis on identifying causal dependencies between variables and further compartmental systems identification.

Kosmerjl *et al.* explore embodied learning of qualitative models. An algorithm called STRUDEL is introduced that utilises inductive logic programming to enable an autonomous robot to discover new concepts by performing experiments in its environment. New concepts are discovered during qualitative model learning. A qualitative method is employed to observe action effects to achieve comprehensible models and to eliminate virtually all effect of numerical observation errors.

Coghill *et al.* enhance the capability of the Morven fuzzy qualitative reasoning system with the features of fuzzy qualitative trigonometry in the context of modelling dynamic systems containing trigonometric relations. This enables, for the first time, these kinds of dynamic system to be modelled and identified by taking advantage of fuzzy qualitative simulation and envisionment capabilities.

Falomir *et al.* investigated fuzzy qualitative approaches for sensor data integration with a focus on distance information. Sensor data is processed against a predefined reference system via a fuzzy dissimilarity checking mechanism, and further interpreted to describe distance information of an environment for robot navigation and for further human-robot interaction.

The second category consists of three application papers in robotics and academic performance evaluation and sensoring information understanding,[15],[23].[2]

Kubota and Yaguchi took the combination of fuzzy control and boltzmann selection into account for qualitative decision making. Continuous human-robot interaction is achieved based on learning on the relationship between humans and their action consequence of behaviors of a robot partner. The research finding is evaluated on a pocket robot partner platform with acceptable results especially on seamlessly reflection of the interaction rules of the physical robot partner.

Zhang *et al.* have proposed a novel covariance tracking algorithm where a fuzzy forgetting factor and random sampling are employed to enhance the real-time performance of object tracking. In the proposed motion tracker, the fuzzy forgetting factor is used to discriminate the false alarm caused by similar objects, while the random sampling is proposed to reduce the computational complexity of covariance tracking.

Finally, Boongoen *et al.* analysed academic performance evaluation using methodology of qualitative link analysis. A graphical representation of systems variables and their relations is constructed; it converts a classification problem of academic performance evaluation into a problem of link-based similarity estimation which is resolved by the proposed fuzzy qualitative reasoning approach.

3. Concluding Remarks

As noted above, the papers in this journal issue have been selected because represent responses to research challenges in FQR and its applications. They provide interesting and insightful solutions to at least some of these challenges; and as with all good research raise as many, if not more, questions than they answer. This is highly encouraging and gives indication that FQR is an exciting research area with the potential to provide high impact solutions. We look forward to seeing this vibrant research community continue to mature and grow; and to a steady increase in the industrial uptake of the technology.

We would like to express our appreciation for the collaboration with the authors who submitted their research to the Journal issue of advances in fuzzy qualitative reasoning. We would also like to acknowledge the support of the Editor-in-Chief, Professor Bernadette Bouchon-Meunier and the reviewers who have helped to improve the quality of the presentations in this journal issue.

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