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Survey Paper

Fuzzy systems, neural networks and neuro-fuzzy systems: A vision on their hardware implementation and platforms over two decades ☆

G. Bosque [a,*], I. del Campo [b,**], J. Echanobe [b,**]

[a] Department of Electronic Technology, University of the Basque Country, Bilbao, Vizcaya 48013, Spain
[b] Department of Electricity and Electronics, University of the Basque Country, Leioa, Vizcaya 48940, Spain

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ABSTRACT

In recent decades, and in order to develop applications covering several areas of knowledge, different researchers have been performing hardware implementations around paradigms such as fuzzy systems, neural networks or systems resulting from the hybridization of the previous two systems, known as neuro–fuzzy systems. Applications have been performed on different types of devices and/or platforms.

The point of view of this paper is focused on a hardware taxonomy (devices where the applications have been implemented) and highlights the characteristics of the different applications covering the aforementioned paradigms done over the last two decades, and the beginning of the current decade. Special mention is made up of reconfigurable devices.

1. Introduction

Since the decade of the 1940s taking into account that in 1943, McCulloch and Pitts (1943) introduced the model of a neuron, to the present day, different paradigms have emerged: these are fuzzy systems, neural networks, genetic algorithms and hybrid systems, these last composed by a combination of the above. They are all encompassed in a more generic concept called Soft Computing.[1] These paradigms have been consolidated in various facets of human knowledge and in several applications in the fields of education, industry, consumption and research.[2] Fuzzy systems or fuzzy inference systems (FISs), based on fuzzy sets and fuzzy logic, work with imprecise reasoning and linguistic rules obtained from the information provided by an expert, leading to systems tolerant of imprecision. Artificial neural networks (ANNs) are computational structures that model the physiological behavior of neurons and connections. The neurons store the knowledge by means of training (learning), obtaining adaptive systems for their environment and tolerant of faults in some of their neurons. Genetic algorithms, based on the theory of evolution, apply genetic inheritance algorithms such as reproduction, crossover, and mutation, to a specific problem.

The scope of the different topics is extensive. Fuzzy systems have proved very useful in support of decision making in areas such as economics (Aluja, 2004; Dompere, 2004; Aliev, 2008) and medicine (Szmidt and Kacprzyk, 2001; Bates and Young, 2003;

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* Corresponding author. Tel.: +34 946014461.
** Corresponding authors.
E-mail address: guillermo.bosque@ehu.es (G. Bosque).
URL: http://www.ehu.es/guillermo.bosque (G. Bosque).

[1] Term coined by Lotfi Zadeh in a course at the University of Berkeley in 1993, to define the computation that emulates the human mind's ability to reason and learn in an environment of uncertainty and imprecision. Subsequently, the meaning of this term has become more widely used.

[2] As interesting historical data, S. Grossberg (USA), T. Kohonen (Finland), and S.-I. Amari (Japan) create the "International Neural Network Society" (INNS) in the spring of 1987. The first conference on neural networks, "IEEE First International Conference on Neural Networks" was held in June 1987 and the number 1, volume 1 of the journal "Neural Networks" appears in 1988. The number 1, volume 1 of the magazine "Fuzzy Sets and Systems" appears in 1978 and the number 1, volume 1 of the journal "IEEE Transactions on Fuzzy Systems" appears in 1993.

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Table 1
Summary which shows the application examples of different paradigms.

Paradigms	Articles		Applications
	Total	Partial	
Fuzzy systems	24	9	Economy (Aluja, 2004; Dompere, 2004; Aliev, 2008) Medicine (Szmidt and Kacprzyk, 2001; Bates and Young, 2003; Chen et al., 2010) Control (Wang and Langari, 1994; Kiriakidis, 1998; Abou, 2011)
Neural networks		8	Robotics (Bekey and Goldberg, 1993; Rao, 1995; Zou et al., 2006) Image (Carpenter and Grossberg, 1992; Egmont-Petersen et al., 2002; Hong et al., 2009 Speech recognition (Othman and Riadh, 2008; Lippman, 1988)
Neuro–fuzzy		7	Pattern recognition (Ray and Ghoshal, 1997; Pal and Mitra, 1999) Robotics (Rusu et al., 2003; Wongsuwarn and Laowattana, 2006) Nonlinear system identification (Babuska and Verbruggen, 2003; Panchariya et al., 2004) Adaptive signal processing (Li and Tsai, 2006; Chabaa et al., 2009)

Chen et al., 2010). Moreover, the application has been remarkable as an alternative control strategy to the classic control techniques for complex systems, which are difficult to model or whose dynamic is poorly understood (Wang and Langari, 1994; Kiriakidis, 1998; Abou, 2011). Neural networks, given their learning ability and adaptability, are applied in areas such as robotics (Bekey and Goldberg, 1993; Rao, 1995; Zou et al., 2006), image processing (Carpenter and Grossberg, 1992; Egmont-Petersen et al., 2002; Hong et al., 2009), and speech recognition (Othman and Riadh, 2008; Lippman, 1988). Within the hybrid systems the neuro–fuzzy systems combine both paradigms; on one hand the system of linguistic rules generated by an expert, on the other hand the learning ability of neural networks applied to this system. The applications include pattern recognition (Ray and Ghoshal, 1997; Pal and Mitra, 1999), robotics (Rusu et al., 2003; Wongsuwarn and Laowattana, 2006), nonlinear system identification (Babuska and Verbruggen, 2003; Panchariya et al., 2004), adaptive signal processing (Li and Tsai, 2006; Chabaa et al., 2009), etc.

Table 1 shows the summary of the aforementioned application examples. The aforementioned references are a sample of a large set of references.

It can briefly be mentioned that one of the main reasons that influenced the success of fuzzy systems, neural networks and neuro–fuzzy systems is their ability to approximate continuous nonlinear functions. In this area within the fuzzy systems, the following works can be cited: Wang (1992), Kosko (1994), Zeng and Singh (1996), Rovatti (1998), Kreinovich et al. (2000), Cao et al. (2001), and Landajo et al. (2001). With regard to neural networks, the following contributions should be highlighted: Stinchcombe and White (1989), Cotter (1990), Hornik (1991), Attali and Pagès (1997), and Castro et al. (2000). On neuro–fuzzy networks, the following references are highlighted: Buckley (1993), Castro (1995), Jang et al. (1997), Nauck and Kruse (1999), Wang and Wei (2000), and Wu et al. (2010). Table 2 shows these contributions.

The different applications of soft computing algorithms have been materialized on different supports over time, depending on the technologies of the moment. The following have been used: general-purpose processors, dedicated processors, dedicated coprocessors, specific designs with Very Large Scale Integration (VLSI) integration scales, either analog or digital or mixed,[3] up to the current reconfigurable hardware (HW) devices. Use has also been made up of multi-processor platforms for systems that require high speed computation and supporting parallel processing, as in the case of neural networks. The use of one or other support has been conditioned by different requirements, among others, power consumption, processing speed, size, portability and cost.

It is in this evolution where reconfigurable device consolidation of type Field Programmable Gate Array (FPGA)[4] (Altera; Xilinx; Lattice; Actel, www.actel.com; Atmel; Cypress; Quicklogic; Achronix) and its high integration, has allowed the implementation of solutions in the environment of soft computing versus focused solutions on specific HW of type Application Specific Integrated Circuit (ASIC)[5] (Atmel; Avago; Elmos; Lsi). Also, it is possible to implement embedded processors (hard-core) (Xilinx, 2007; ARM, 2001; Actel-ARM) and instantiated (soft-core) (Xilinx, 2008; Altera, 2004; Actel, www.actel.com/products/mpu/coremp7/) with other HW functional blocks on these devices. This leads to the so-called System-on-a-Programmable Chip (SoPC) being able to integrate complete systems on one device. All these make the search for efficient implementations in the area of fuzzy inference systems in neural networks and neuro–fuzzy networks on these devices particularly attractive. This paper aims to provide a historical overview of this search for the aforementioned systems.

The paper is structured as follows: Section 2 reviews the first HW implementations of fuzzy systems and neural networks. Section 3 shows a generic classification of HW implementations of the fuzzy, neural and neuro–fuzzy systems. Sections 4–6 review the implementations of fuzzy, neural and neuro–fuzzy systems respectively on different types of devices. Finally, Section 7 summarizes the conclusions of the work. The bibliography shows the books and articles consulted throughout this work.

2. First implementations of fuzzy, neural and neuro–fuzzy systems

The last two decades have been marked by a great evolution in the field of computer hardware for fuzzy, neural and neuro–fuzzy systems. The solutions have been provided on analog HW, digital HW and mixed digital/analog HW. The digital hardware is what has presented the most important development due to the consolidation of programmable or reconfigurable devices, mainly in the FPGAs. The high integration density and the power introduced by the parallel structures achieved by this technology have enabled implementations of fuzzy inference systems with a high number of fuzzy rules, neural networks with a large number of layers and neurons, including learning algorithms, and finally, neuro–fuzzy systems based on fuzzy rules and endowed with learning mechanisms of the same type as those used in neural networks.

[3] This paper employs the term “mixed” instead of “hybrid” to avoid confusion with the term applied to “hybrid system”.

[4] Invented by Xilinx in 1984.

[5] The company Ferranti, around 1980, produced the first gate array known as ULA (Uncommitted Logic Array – Matrix Logic not Fixed) and can be regarded as the pioneer in this technology.