Fuzzy Computer Architecture Based on Memristor Circuits

Martin Klimo
Faculty of Management Science and Informatics
University of Zilina
Zilina, Slovakia
martin.klimo@fri.uniza.sk

Ondrej Such
Mathematical Institute
Slovak Academy of Sciences
Banska Bystrica, Slovakia
ondrej.such@gmail.com

***Abstract*— von Neumann computer concept is approaching its limits and new computing paradigms are needed. This paper introduces a fuzzy computer architecture based on memristor circuits. The new concept offers naturally parallel architecture that unifies memory and data processing. We discuss both application specific and general purpose computing. We conclude with an outline of a research roadmap to bring the concept into practical realization.**

Keywords* - *unconventional computing; fuzzy logic implementation; memristor.

I. INTRODUCTION

In May 2011, FET Proactive Unit of DG-INFSO EC has published a document [1] that presents challenges for 2011-12 period as a result of a broad discussion within ICT community. The idea threading through several essays in this brochure is that von Neumann computer concept is reaching its limits and new computing paradigms are needed. When a program is stored in memory, its instructions need to be transferred, along with the data, into the CPU for execution. This introduces performance barriers: firstly, disjoining processing from memory and secondly, inherent serialization of program execution. These problems motivate research into new computing concepts.

Promising solutions seem to be the quantum computing and biomolecular/biocellular computing. Quantum computing is well covered by FET projects, and, even in May 2011, there was announced a sale of the first commercial quantum computer [2]. In 2010, the BACTOCOM FET Proactive project [3] was also launched focussing on bio-computer prototyping based on population of E. coli bacteria and following in 2011 by COBRA FET Proactive Coordination Action [4]. Although these technologies are promising, they are not mature enough.

Nanotechnology promises a new way to overcome performance limitations mentioned above. In 2008, the HP Lab realised a memristor [5], a two terminal circuit element. forecast by Leon Chua in 1971 [6]. This element is able to change its resistance between high and low resistance states. It does so under bias and in effect it “remembers” charge that has flown through it. Moreover, the change is non-volatile, meaning no energy is needed for memristor to maintain its state. Nanoscale has proven crucial for the functioning of the device since in this realm enormous electric fields can be realized with low voltage. . Energy savings and higher densities can be obtained by non-volatile memristor memories announced for market in 2013 [7]. They can also bridge the distance between processing unit and the memory [8]. But, memristor crossbar can unify the memory and the processing unit together. Nowadays we can find two approaches how to do this. The first idea is to use memristors in the role of a synapse within a neural network. This approach is studied by ERC Starting Grant NANOBRAIN [9] since 2010. The second idea [10] is based on the fact that Boolean implication can by executed by material implication, where the logic value is expressed by the memristance and not by the voltage. This allows one to compute Boolean logic functions [11] by memristor crossbar.

In the rest of our paper we present our new approach based on fuzzy logic circuits instead of binary logic circuits. Memristor implementation of fuzzy logic functions not only brings energy savings, but it naturally joins computation and memory functions and thus creates brain-like computing architecture.

In the next section we review the basic building blocks for fuzzy logic circuits. In section three we describe an application-specific fuzzy architecture that parallels currently employed fuzzy controllers. Section four describes a general-purpose fuzzy logic computer whose main distinguishing feature is reconfigurability. We conclude we propose a research roadmap that would bring the new architecture into reality.

II. FUZZY LOGIC IMPLEMENTATION BY MEMRISTORS

We have found [16] that elementary circuits with memristors can compute min (Figure 1), max, avrg functions and in synchronised mode (similar to [10]) the implication as well in voltage domain.

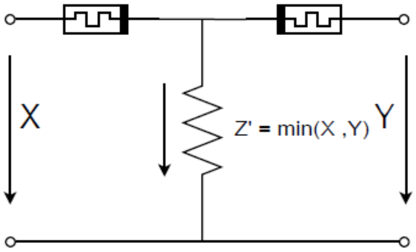

Figure 1. Example of a fuzzy function implementation.

Hardware implementation of min, max functions is not a new idea and fuzzy logic circuits based on CMOS, FET [17] [18] or FPGA [19] implementations have been used. However, there are two principal advantages of memristor based implementations:

1. Circuit uses only energy of its inputs and no extra source of energy is needed compared with the transistor based implementations mentioned above.
2. Memristor implementation introduces also a memory feature of these elementary circuits. This property is based on dynamic behaviour of memristors and it needs further research.

These three functions (min, max, avg) allow only building of a monotone fuzzy logic system [12]. Using clock pulses for implication or using CMOS invertors for negation, the Gődel logic can be implemented. This has a significant impact on the fuzzy computer architecture and all possibilities have to be investigated within the project for which we are looking for partners. Here we present an asynchronous architecture using the property of de Morgan law that the dual logic function with inverted inputs gives the inverted function. This dual system approach allows simpler implementation because invertors are located only in the first stage of min, max, avg based circuit. This means that energy source is needed only at the border of the fuzzy logic circuit and the rest of circuit is passive and voltage values are continuously recalculated as fuzzy logic functions when nonzero voltage inputs occur.

We can conclude that memristor-based elementary fuzzy functions with dual system approach allow building general problem solving machines like today’s digital computers.

III. APPLICATION SPECIFIC FUZZY COMPUTERS

Thirty years of fuzzy systems applications show a big market potential of application specific fuzzy logic circuits. Capability of high density integration makes them suitable for control functions in daily life in applications like phones, cameras, etc. A general architecture of such a fuzzy computer is well known fuzzy system architecture, as shown in Figure 2.

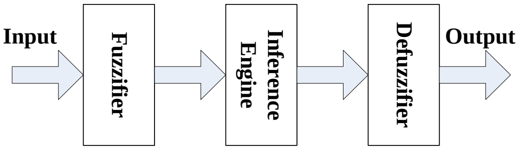

Figure 2. Application specific fuzzy system architecture.

Min, max, avg functions can be applied in all of blocs in the fuzzy system; anyhow, we will concentrate on **Inference engine,** which is a fuzzy logic circuit itself.

Although fuzzy logic applications are often times ahead of theory development, today's fuzzy logic stands on sound mathematical foundations that are continuously being extended. Fuzzy logic allows one to systematically approach solving problems dealing with „uncertainty“, in much the same way as two-valued logic captures manipulation of „certain“ information. This is the area where human are still order of magnitudes faster than currently used computers. However, should fuzzy logic systems approach complexity of human brain, they cannot be emulated on a von-Neumannn computer. In their implementation, one needs to use blocks that can *naturally* execute elementary fuzzy logic functions and allows them to connect them into larger circuits.

One of the main tasks in a fuzzy system design is optimization of fuzzy logic circuit for a particular application. In a small system the set of implications can be explicitly proposed, but no optimization method is available for large fuzzy circuits. Promising results give metaheuristics like evolution programming, genetic programming, fractal structures and so on.

Creating fuzzy logic functions by memristor network topology evokes reminiscences to analog computing. Comparing memristor based computing with quantum or biocellular computing the memristor technology is more mature and several feasible approaches (metal-oxid, ferro-magnetic, grapheme-oxide) for implementation exist.

Min, max functions in Gődel logic is just one example of t-norm and co-norm in fuzzy logic. On the other side they are examples of fuzzy logic functions that are easily implemented by memristors. This gives rise to the question about position of Gődel logic within the general framework of fuzzy logics for applications.

IV. GENERAL PURPOSE FUZZY COMPUTERS

A general-purpose fuzzy computer requires means to reconfigure its circuits, because, like in the analog computer, the program is given by the circuit topology and the initial state of the system. A rule generator, possibly controlled by a CPU/GPU computer, reconfigures memristor switches in fuzzifier, inference engine and defuzzifier as shown in Figure 3.

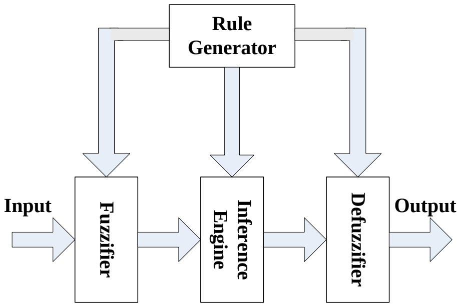

Figure 3. General purpose fuzzy system architecture.

Then programming, compiling and program execution is a process in which topology of fuzzy logic circuit is designed and parameters of fuzzifier and defuzzifier are specified. In this phase fuzzy computing keeps continuity with classical computing where programs are written by a human expressing given logic requirements. This approach can build on previous works on the fuzzy logic programming [13] and Fuzzy Prolog-like program languages [14] or domain specific languages.

This means that programming can be executed on a classical computer with interfaces into a general structure of reconfigurable memristor network. Memristor crossbar seems be a suitable element to do this, but many questions on the implementation are still open.

As a starting point the following fuzzy computer architecture (shown in Figure 4) may be assumed.

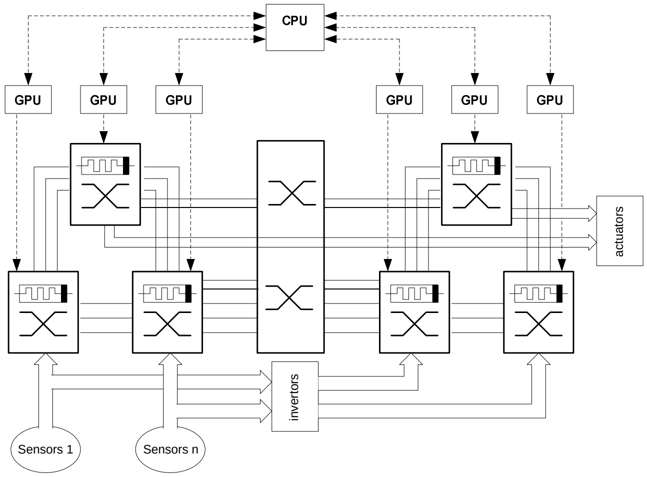

Figure 4. Fuzzy computer architecture, processing sensor inputs on memristor crossbars and yielding actuators

This is two-layer architecture. At the bottom there are memristor crossbars for real time processing with input-output interfaces from sensors – into actuators, as well as invertors for the dual system. We can see dual logic architectures consisting of two "hemispheres". If more crossbars are required to create one hemisphere than may be given by capacity constraints, sense domain separation or hierarchy needs [15], then additional switches may be needed. Also a switch that will connect the corresponding functions in both hemispheres ("Corpus Callosum") belongs to this layer. At the top layer there are classical computers (CPU/GPU) that generate topology of memristor network within crossbars and switches regarding required fuzzy logic functions given by logic program. This topology may be fixed; anyhow we assume that local rules within one crossbar can be adapted by program in corresponding GPU (short-term plasticity) while the long-term strategies (like supervised learning) will be distributed from the supervising CPU on the top.

V. CONCLUSION

Fuzzy logic has been applied in practice for several decades. Memristor technology, despite being just a few years old, is progressing rapidly, and first memristor memories will be commercialized within a year. In order to combine them, and realize aforementioned fuzzy logic computers, a natural research roadmap can be outlined:

1. Adaption of fuzzy logic system to memristor technology
    a. suitability of Gődel logic from applications point of view
    b. evaluation of different memristor technologies (unipolar, bipolar, metal oxide, ferro-magnetic, etc)
    c. theoretical limits of fuzzy logic memristor circuits
    d. influence of memristor threshold effect on fuzzy computation
    e. composition of logic functions
    f. properties of self-referencing fuzzy logic functions (delay and synchronisation)
2. Fuzzy Prolog like programming languages and corresponding compilers have to be developed to allow programmers write programs in digital computer style to create structures in fuzzy logic networks
3. Applications development
    a. simple programs for architecture benchmarking
    b. evolutionary and genetic programs for more complex brain-like applications

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