CMOS Fuzzy Analog Controller with Digital Programming.

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Abstract: - In this work a programmable system for the processing with fuzzy logic is presented. The fuzzy algorithm is fully analogical and can be programmed for different applications using digital – analog converters (DAC). The circuit is biased with 3V and it is designed for a 1.5 μm CMOS technology process. The results of the simulation show the correct operation of the circuit.

Key-words: Fuzzy logic, analog design, current-mode, VLSI

1. Introduction.

The fuzzy logic is used at this moment in a wide variety of industrial applications: control, robotics, communications, medical diagnosis, etc. [1]. This use has given like result the increase in the investigation and the development of new applications using this paradigm, and obviously the evolution of the fuzzy systems.

Many fuzzy systems used at present in industrial applications are implemented with digital components, the main reason is that these offer immediate benefits like their programming, which is necessary in systems variants in the time; in addition they present a more easy connection with other systems of digital processing. But the use of digital fuzzy systems have some disadvantages, for example, the synthesis of a *maximum* function in a unit CMOS uses around one hundred transistors, and in addition they have the necessity to use A/D and D/A converters to communicate with the real world [2]. On the other hand, the fuzzy logic is intrinsically more similar to the multivalued and continuous analog world that the digital one, reason why resorting to analogical techniques offers potentially better characteristics than digitals, such as one better "silicon area/inference speed" ratio, besides eliminate the necessity of interphases A/D and D/A [3]. The new techniques of analog design offer in addition the possibility to the digital or continuous programming. The disadvantage of the analog systems is in the difficulty to obtain precision in the processing due to the mismatches of the devices, which can be diminished with design techniques.

In this work, the proposed system takes the advantages from the two techniques of design, the digital and the analog one. The fuzzy algorithm is completely analog to reduce integration areas and to also provide a greater speed of processing annexed programming by means of digital-analogical converters (DAC) to offer an ample range of applications of the fuzzy system.

2. Fuzzy logic systems.

Figure 1 shows the basic structure of a fuzzy system, it consists of the following components:

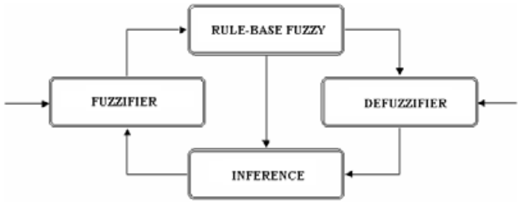

Fig. 1 Structure of a fuzzy model.

- *Fuzzifier*: It transfers the input data to fuzzy sets. Between the functions of membership, the more used are: triangular, trapezoidal and Gaussian [5].
- *The rule-base fuzzy*: It is a set of fuzzy rules in form of IF(condition)-THEN(action) clauses, in the form:

  $$R\!: IF\ X_1\ is\ Ai_1\ and\ .....and\ X_n\ is\ Ai_n\ THEN\ y\ is\ C_i$$

  Where X_j ($j = 1...., n$) are the input signals representing antecedent (premises), "*y*" is the output, *Aij* are linguistics variables and *Ci* are the consequent values [3]. This module stores the rules that contain the heuristic knowledge and qualitative on that the actions will be based.
- *Inference*: It is a decision logic, which uses the rules of the previous process to produce fuzzy outputs [5]. Its main function is in the calculation of the degree of activation of each rule, as well as the aggregation of these [2]. The more used inference processes, have been proposed by Mamdani and Sugeno [4].
- *Defuzzifier*: It produces a not-fuzzy action of the inferred fuzzy output.

The efficiency of a fuzzy controller depends of a careful selection of the inference mechanisms like of the structure of the circuit that makes each block [6]. The strategy of Mamdani is based on a method known like MAX-MIN, here the implication is made by means of minimum circuits and the aggregation by maximum circuits. Other strategies similar to the proposal of Mamdani exist, for example; the strategy MAX-PROD, strategy SUM-PROD, etc [7]. As shows in figure 2, the consequent in the method of Mamdani are represented by fuzzy sets. From a point of view of design of integrated circuits, the definition of the consequent variable as a fuzzy set is very expensive in terms of area and time.

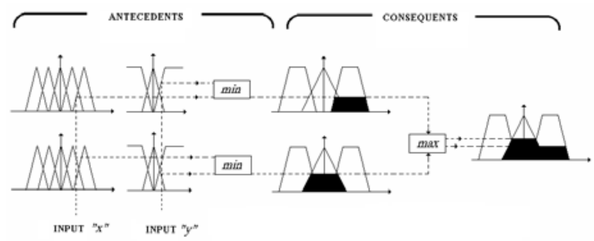

Fig. 2 Mamdani mechanism.

The hardware is reduced significantly if the value of the consequent is defined by some parameters instead of fuzzy sets. These parameters will concentrate the information that a function of membership provides through a fuzzy set. The method that uses this type of consequent knows like the method Takagi and Sugeno [4], which is in figure 3. However, if these parameters we took them like constant values, the resulting method is known like method Sugeno order zero or Singleton [2], where the constant values are known like fuzzy impulses or Singletons. The main characteristic of this method is the easy thing that is its accomplishment in circuits VLSI.

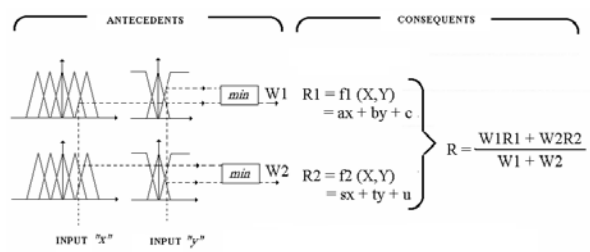

Fig. 3 Takagi and Sugeno mechanism.

The global output of the fuzzy controller using the method of Sugeno of order zero will be given by the equation 1.

$$Output = \frac{\sum_{i}^{n} h_i \cdot c_i}{\sum_{i}^{n} h_i} \qquad (1)$$

Where:

h_i = Degree of activation.
c_i = Consequent.

In [8] the implementation CMOS of the product between the corresponding degrees of activation and its consequent ones was carried out by means of a multiplier circuit of four quadrants, in this work the multiplier is replaced by scale up/down circuits, these circuits are more simple to design and make easy the digital programming [9], in addition, the use of these circuits reduces the integration area in notable way.

3. Functional blocks.

The functional blocks for the implementation of the fuzzy controller of the type Takagi and Sugeno, are the following:

- *Membership function circuits (MFC´s)*: These circuits represent the membership functions of the antecedents, providing the degree of connection between the signals of input of the controller and the antecedents of the rules [2].
- *Minimum/maximum circuits (MIN/MAX)*: They connect the antecedents of a rule, calculating the degree of activation of each rule [3].
- *Consequent scale up/down circuit (scaler)*: This circuit weights the degree of activation of each rule by its corresponding consequent value [3].
- *A divider*: Necessary to obtain the non-fuzzy output.

4. CMOS implementation of functional blocks.

A) Membership function circuits.

Exists several analog implementations to construct membership functions [1]-[10] nevertheless these present difficult to represent functions that are not triangular. Figure 5 illustrates a MFC that can produce triangular and trapezoidal functions [11]. The selection of the function will depend on the value of the saturation current (I_{sat}). The transistors T1 and T2 along with the M1 mirror work like a rectifier of current for the difference of the signals Iin-Iaux. When this difference is positive, T2 is off, T1 is leading and produces an output of current of the M1 mirror, this current is a copy of - (Iin-Iaux) that will control the M2 mirror (that as well determines the slope of the function of membership). On the contrary when Iin-Iaux is negative, T1 is off, T2 leads and the M2 mirror will be controlled by a copy of the difference of input currents.

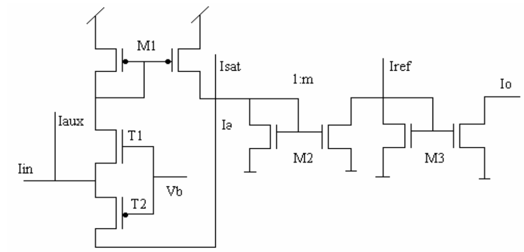

Fig. 5 Membership function circuit.

The value of the slope will be able to be fixed by means of the selection of the geometric ratio of the transistors that form the M2 mirror. As it is seen in the circuit, a Iref current is added before the M3 mirror, reason why the output current will be expressed as defined in [3]. The figure 6 show the MFC with programming made by means of digital-analogical converters (DAC), based on current mirrors [3]. Two of them fix the values of positive and negative Iaux to fix as well the axis central of the fuzzy set, another one is in charge of the saturation and the last two are in charge to make the scaling of the slope of the function. The DAC associated to slope 1 makes the single scaling of one of the sides of the fuzzy set and the DAC associated to slope 2 makes the scaling of sides of the set at the same time. Finally the transistor connected in diode of this converter makes the difference limited with Isat. The inverter who is used to the input is for avoiding bias in the generation of Iin and Iaux due to the great changes of voltage in the node of input [11]. In figure 7 are the used parameters to identify a symmetrical trapezoidal.

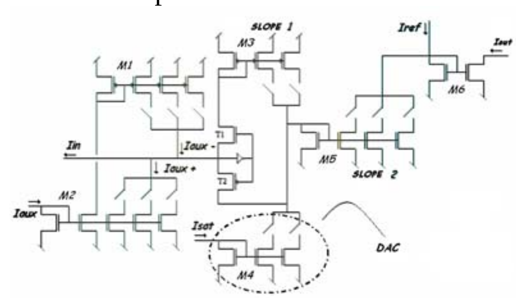

Fig. 6 Programmable MFC.

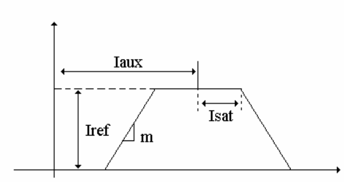

Fig. 7 Parameters that represent a trapezoidal function.

B) Minimum circuits.

Figure 8 shows the scheme of a circuit for the calculation of the maximum values for multiple inputs, proposed by Huertas in [13]. The function of this circuit within a fuzzy controller is the one to make a minimum connection between the antecedent rules, this function MIN is obtained by means of the laws of *De morgan*.

$$MIN(I_1,\cdots,I_n)=MAX(I_1,\cdots,I_n) = I_{ref}-MAX(I_{ref}-I_1,\cdots,I_{ref}-I_n) \qquad (2)$$

The transistors T_i act like voltage followers competing to fix the value of the voltage to their node source, necessary so that its corresponding transistor M_i operates in saturation, thus leading, the current of entrance.

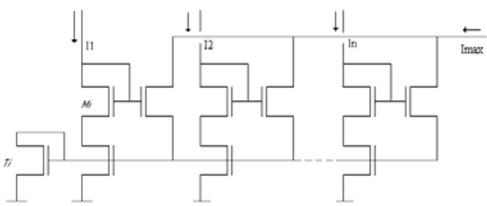

Fig. 8 Multi input MAX circuit.

C) Divider circuit.

Within the design VLSI, the division it is the algebraic operation more difficult to make, and although in the state of art exists an ample range of divider circuits [9], [14]. In the design of this controller the division was made by means of a multiplier of four quadrants reported in [8] connected as it is in figure 9.

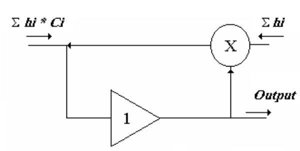

Fig. 9. Divider circuit.

By I complete, this circuit is standardized with a current of 20 µA, reason why it will be necessary to destandardized to obtain the global output.

5. Simulations results.

The simulations that are next were obtained with the archives of extraction of layouts of each circuit, the layouts were made in L-edit pro V.8.

In table 1 are the dimensions of the transistors that compose the circuit of membership functions, MFC.

Table 1. Dimensions of the TMOS of the MFC.

Rectifier of current	***Lenght.***	***Wide.***
T1	4 µ	20 µ
T2	4 µ	27.8 µ
Nmos (Inv).	4 µ	28 µ
Pmos (Inv)	4 µ	77.6 µ
IAUX +	***Lenght.***	***Wide.***
M1-m1'	4 µ	27.8 µ
m1''	4 µ	50.5 µ
m1'''	4 µ	100 µ
IAUX -	***Lenght.***	***Wide.***
m2 – m2''	4 µ	20 µ
m2'''	4 µ	40 µ
m2''''	4 µ	81.5 µ
Slope 1	***Lenght.***	***Wide.***
M3, M3'	4 µ	27.8 µ
M3''	4 µ	51 µ
Saturation	***Lenght.***	***Wide.***
M4, M4'	4 µ	20 µ
M4''	4 µ	40 µ
Slope 2	***Lenght.***	***Wide.***
M5, M5'	4 µ	20 µ
M5''	4 µ	40 µ
M5'''	4 µ	81.5 µ

In figures 10, 11, 12 and 13 are the programmings for the central axis, saturation, and the slopes that can take each one from the MFC´s that compose the controller. Figure 10 show four values of the fourteen possible ones that it can take the position from the central axis, with Iaux of 2 µA. In figure 11 are the four possible values that can take the parameter from saturation when Isat is of 2 µA. In figure 12 are three of the seven possible values that can take the parameter from slope (both sides simultaneously). In figure 13 is the possibility of the individual programming of slopes of the function of membership.

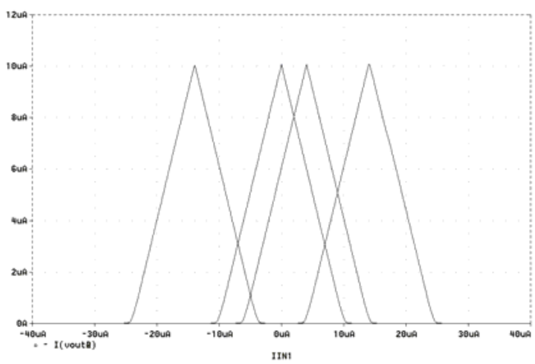

Fig. 10 Programmming of the central axis.

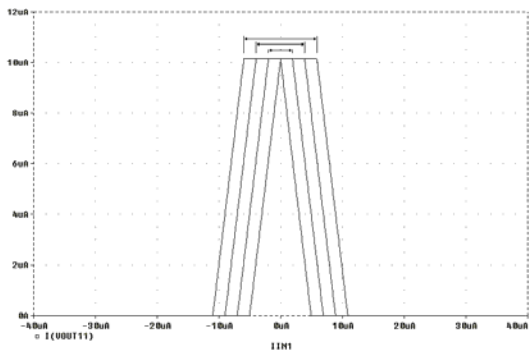

Fig. 11 Programming of the saturation.

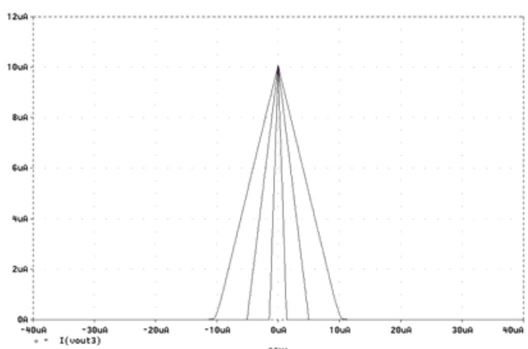

Fig. 12 Programming of the slope.

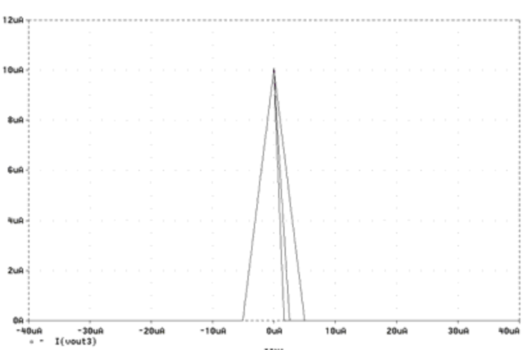

Fig. 13 Programming of the slope.

The design of the fuzzy controller programmable was made with base in the architecture of the figure 14. This consists of two inputs represented by two pulses of current with a value of 2μA p-p, five circuits of membership functions for each input, 25 minimum circuits for the 25 possible combinations, as showed in table 2, five circuits to represent each consequent, and a circuit divider to represent real the global output.

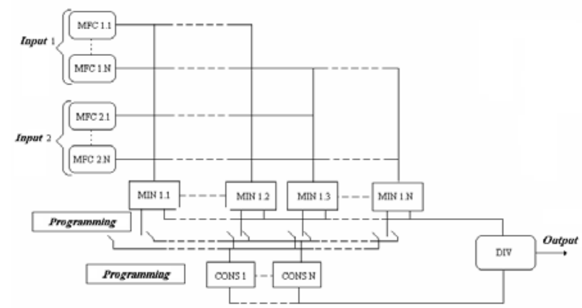

Fig. 14 Structure of fuzzy controller.

Table 2. Rule-Base fuzzy.

y / x	**+ NEG**	**NEG**	**ZERO**	**POS**	**+ POS**
+ NEG	+ NEG	+ NEG	+ NEG	NEG	ZERO
NEG	+ NEG	+ NEG	NEG	ZERO	POS
ZERO	+ NEG	NEG	ZERO	POS	+ POS
POS	NEG	ZERO	POS	+ POS	+ POS
+ POS	ZERO	POS	+ POS	+ POS	+ POS

As it is possible to be seen of figure 14, in addition to the programming in the antecedent part, also the rule-base can be programmed for a wide range of applications. In figures 15 and 16 are to the MFC´s for the inputs “x” and “y” respectively. It is possible to emphasize that the election as much of the rule bases as of the inputs was arbitrary, single for test of the controller.

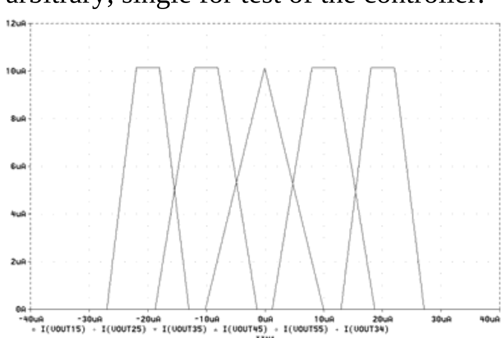

Fig. 15 MFC´s for inpu t”x”.

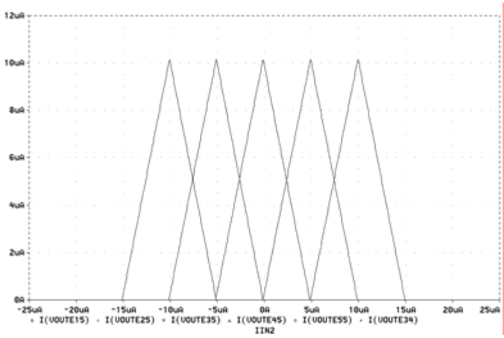

Fig. 16 MFC´s for the input "y".

In table 3, are the four rules activated for a inputs of and 2μA y 0μA. The values showed are the degrees of activation of each rule.

Table 3.Degrees of activation.

Inputs	***Pulse = 2μ***	***Pulse = 0μ***
Input 1	1.25μ, 7.85μ	10μ
Input 2	4.00μ, 5.56μ	10μ

The obtained values for $\sum h_i$ and $\sum h_i \bullet c_i$ are (11.9905μ and 9,993μ) and (7.5236μ and 4.9677μ) respectively, and with them the total output is obtained, which is in figure 20 after of the desfuzzification.

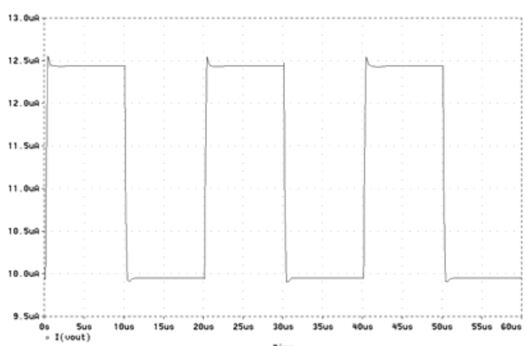

Fig. 17 Final output of the fuzzy controller.

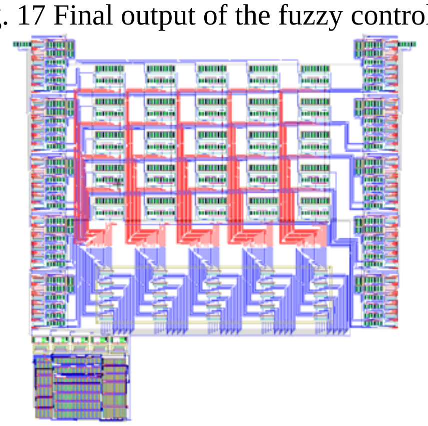
Fig. 18 Layout of the fuzzy controller.

Finally, in figure 18 is the layout of the fuzzy controller and in table 5 a comparison becomes of the controller proposed with other controllers already made.

Tabla 4. Comparison of designed controllers.

Charac teristic	Manares i	Guo.	Rguez Vázquez .	Baturon e Sánchez	Proposal
Complexity	9 rules 2 inputs 2output s	13 rules 3 inputs 1 output	16 rules 2 inputs 1 output	9 rules 2 inputs 1 output	25 rules 2 inputs 1 output
Technology	0.7 μA	2.4 μA	1 μA	2.4 μA	1.5 μA
Consumptio n of energy	44 mW	550 mW	8.6 mW	12 mW	13.5 mW
Voltaje of polarization	5 V	10 V	5 V	5 V	3 V
Input-Output	V/V	V/V	V/I	I/I	I/I
Area	1.9 mm^2	16 mm^2	1.6 mm^2	1.2 mm^2	2 mm^2
Inference speed		6 MFLIP S	2.5 MFLIP S	0.5 MFLIP S	2 MFLIP S
Commentar y		Progra m	Progra m	Progra m	Progra m

6. Conclusions.

In this work the design of a fuzzy controller made with technology MOS appeared in current mode. For the design of the circuits were analyzed the characteristics of the different methods from processing, selecting that provides a greater number of advantages with relation in "area of the chip/Speed of inference" and that is feasible their physical accomplishment in VLSI for applications in real time. The controller has the following characteristics: two inputs and one output with programmable functions of membership. The programmable climbing circuits to determine to the consequent ones like diffuse impulses eliminate the necessity of multiplying circuits to calculate the numerator in the defuzzification process, which provides a saving in the area of the chip. Taking into account the comparisons from table 4, the design of this fuzzy controller, it has the characteristics to occupy a silicon area and to have a consumption of power smaller than a digital accomplishment, in addition of which potentially it has greater speed of processing. The programmability allows that it is possible to be used for different applications such as adaptive filtering and control.

7. References.

[1] Laurent Lemaitre, Marek J. Patyra, Daniel Mlynek, “Análisis and design of CMOS fuzzy logic controller current mode,” IEEE J. Solid-State Circuits, vol. 29, no. 3, pp. 317-322, Marzo 1994.

[2] Iluminada Baturone, Santiago S. solano, Angel Barriga, Jose L. Huertas, “Implementation of CMOS fuzzy controllers as mixed-signal integrated circuits,” Trans. Fuzzy Systems, (Special Issue on Hardware Implementations), vol 5, no. 1, pp. 1-19, Febrero 1997.

[3] Jose. L. Huertas, Santiago S. Solano, I. Baturone, Angel Barriga, “Integrated circuit implementation of fuzzy controllers,” IEEE J. Solid-State Circuits, vol. 31, no. 7, pp. 1051-1058, July 1996.

[4] D. Mlynek, “Fuzzy logic sistems,” Design of VLSI Systems.

[5] Angel Torralba, Jorge chavez, Leopoldo G. Franquelo, “Circuit performance modeling by means of fuzzy logic,” IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 15, no. 11, Noviembre 1996.

[6] Iluminada Baturone, Santiago S. solano, Jose L. Huertas, “Towards the implementation of adaptive fuzzy systems,” IEICE Trans. On Fundamentals of Electronics, Comunications and Computer Sciences, vol. E81-A, no. 9, pp. 1877-1885, Septiembre 1998.

[7] M. J. Patyra, D. M. Mlynek “Fuzzy Logic: Implementation and Applications”

[8] Alejandro D. Méndez, G. Espinosa. F. Verdad, Héctor P. Meana, J. C. Sánchez García, Gonzalo D. Sánchez, “ A CMOS current-mode analog fuzzy adaptive filter”, Journal of Signal Processing, vol. 5, no. 4, pp. 311-318, july 2001, Japan.

[9] Iluminada Baturone, Santiago S. solano, Ángel Barriga, Carlos J. Jiménez Fernández, Diego R. López, “Microelectronics Design of Fuzzy Logic-Based Systems”.

[10] J. L. Huertas, Iluminada Baturone, Santiago S. solano, Ángel Barriga, “Building blocks for current-mode implementation of VLSI fuzzy microelectronics,” Fifth intenational Fuzzy Sys-tems Association World Congress (IFSA’93), vol. 11, pp. 929-932, Seoul – Korea, Julio 4-9 1993.

[11] J. L. Huertas, Iluminada Baturone, Santiago S. solano, Ángel Barriga, “A hardware implementation of fuzzy controllers using analog/digital VLSI techniques,” Computers & Electrical Engineering, vol. 20, no. 5, pp. 409-419, september 1994.

[12] Z. Wang, “Novel pseudo RMS current converter for sinusoidal signals using a CMOS precisioncurrent rectifier,”IEEE Trans. Instrum. Meas., vol. 39, no. 4, pp. 670-671, 1990.

[13] I. Baturone, A. Barriga, J. L. Huertas, “Multi-input voltaje and current-mode min/max circuits,” 3rd. International Conference on Fuzzy Logic, Neural Nets and Soft Computing (IIZUKA´94), pp. 649-650, Iizuka – japan, Agosto 1-7, 1994.

[14] I. Baturone, S. Sánchez Solano, J. L. Huertas, "CMOS Design of a Current-Mode Multiplier/Divider Circuit with Applications to Fuzzy Controllers," Analog Integrated Circuits and Signal Processing, Kluwer Academic publishers. vol. 23, no. 3, pp. 199-210, Junio 2000.