ARCHITECTURE PROPOSAL OF ANALOG INTERVAL TYPE-2 FUZZY LOGIC INFERENCE SYSTEMS

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Abstract— *This paper proposes an architecture for analog implementation of a Type-2 Fuzzy Inference Circuit, which is the main block of the Interval Type-2 Fuzzy Logic Controller (IT2FLC) chip. This architecture is composed of Minimum (Min) and Maximum (Max) circuits. The former are used to combine the antecedents of the rules and the later are used to combine the consequents currents of the rule (from the type-2 fuzzifier circuit). These circuits operate in current mode, with a supply voltage of 3.3V. The proposed architecture (which consists of two inputs with two membership functions for each one, four rules, and one output with three membership functions) was validated through Mentor Graphics simulation in a 0.35µm CMOS technology. The Mentor simulation result of the proposed architecture was compared with similar a Type-2 Fuzzy Inference System simulated in Interval Type-2 Fuzzy Logic Toolbox from Matlab.*

Keywords: *Interval Type-2 Fuzzy Inference Systems, Architecture FIS, Interval type-2 fuzzy logic controller.*

1. INTRODUCTION

In 1975, Zadeh introduced the concept of type-2 fuzzy sets [Zadeh, 1975], whose main feature is the ability to model uncertainty. In 1976, Mizumoto and Tanaka presented studies on the operations of type-2 fuzzy sets and their membership functions. In 1977, Niemien presented the algebraic structure of type-2 fuzzy sets with more details. In the following years, no relevant studies were found involving the type-2 fuzzy sets [Mendel, 2001]. The type-2 fuzzy logic was again approached by the scientific community in the late 90s with the work of Karnik and Mendel [Karnik and Mendel, 1998; MENDEL, 2001]. In these works, the complete theory of the Type-2 Fuzzy Inference System (FIS) was presented, including the operations, the type-reducing and defuzzification methods. In 2000, Liang and Mendel developed the theory of the Interval Type-2 FIS and showed the design of a full Interval Type-2 FIS [Liang and Mendel, 2000]. Moreover, many applications presented showing the superior performance of the SIF interval type-2 and its ability to handle with uncertainty, such as nonlinear time-varying channel equalization [Liang and Mendel, 2000a], time series forecasting [Liang and Mendel, 2000b], encoded video stream encoded classification [Liang and Mendel, 2000c], among others. But the main problem of the Interval Type-2 FIS is its large computational requirement for the operation of type-reducer. In order to solve this problem, Wu and Mendel developed the method of uncertain bounds [Wu and Mendel, 2002], which allowed rapid execution of type-2 FIS and its application in the industrial applications and real-time control systems. Besides these applications, the type-2 FIS was also used in the following application areas: computer science, medical diagnosis, pattern recognition, mathematics, among others [Dereli et al, 2011; Castillo et al, 2008]. In type-1 fuzzy set, the membership grade for each element is a crisp number, as presented in Figure 1a. The membership function (MF) of type-2 fuzzy set has a footprint of uncertainty (FOU). The FOU of type-2 fuzzy set is bounded by an upper and lower type-1 membership function (MF) denoted by $\overline{\mu_A}$ and $\underline{\mu_A}$, respectively. The secondary MF of type-2 fuzzy sets can be uniform or non-uniform, as shown in Figure 1b. The Interval Type-2 Fuzzy Inference Systems are composed of uniform secondary membership function. It is used to reduce the computational complexity of Type-2 FIS [Mendel et al, 2002; Mendel, 2007; Hagras, 2007].

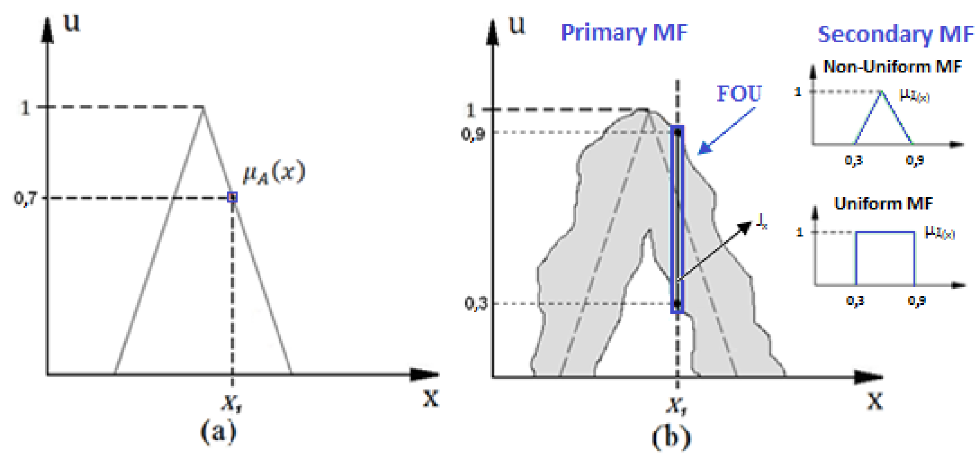

Figure 1. Membership function (a) Type-1 fuzzy set (b) Type-2 fuzzy set.

The diagram of Interval Type-2 Fuzzy Inference System [Choia et al, 2009] is presented in Figure 2. It consists of a fuzzifier, an inference engine, a rule base, a type-reducer, and a defuzzifier. The fuzzifier converts the crisp inputs into a type-2 fuzzy set. In the inference engine block, type-2 fuzzy set activates the rule base to generate output type-2 fuzzy sets. The type reducer converts an interval type-2 fuzzy set into a type-1 fuzzy set. The defuzzifier produces the crisp output.

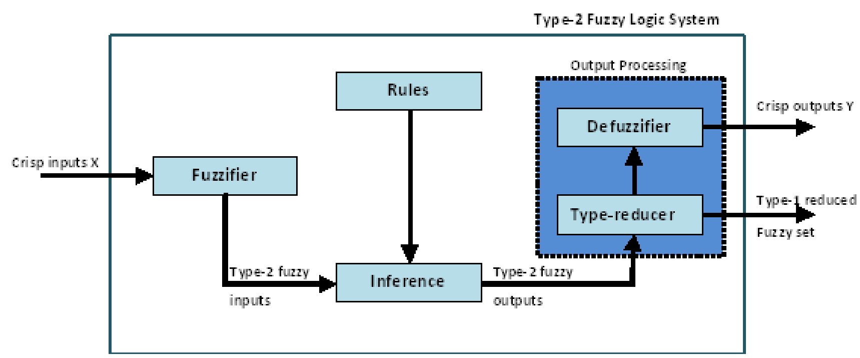

Figure 2. Structure of Interval Type-2 Fuzzy Inference System.

This paper presents the architecture of an Interval Mamdani Type-2 Fuzzy Inference System. This inference system is the main block of a two input and a one output type-2 fuzzy logic controller (with four rules). It was designed in current-mode AMS CMOS 0.35μm technology. The operation of all circuits presented in this paper was verified through the Mentor Graphics simulation.

Finally, the simulation result of the proposed architecture was compared with an equivalent inference system simulated in the Interval Type-2 Fuzzy Logic Toolbox of Matlab.

This paper is organized as follows: Section 2 presents the proposed architecture of Type-2 fuzzy inference systems, as well as the circuits that compose them. Section 3 presents the Mentor simulation results of the proposed architecture and the Matlab simulation results used to validate the architecture, and finally, section 4 presents the conclusions of the proposed work.

2. PROPOSED ARCHITECTURE INFERENCE

This topic presents the proposed architecture to develop the analog inference circuit of the interval type-2 fuzzy controller chip. The proposed architecture (Figure 3) has the following specification:

-Two inputs and one output, operating in current mode;

-Mamdani interval type-2 fuzzy inference system with singleton inputs and t-norm (minimum) t-conorm (maximum) operators.

The input of type-2 inference circuit is composed of the fuzzifier circuits (FOU) that generates type-2 membership function, as presented in the previous paper [Rocha Rizol et al., 2011].

Figure 4 shows the diagram that represents the architecture (Figure 3) of the Mamdani interval type-2 fuzzy inference systems with singleton input, two type-2 membership functions in input x_1 ($\tilde{F}_{1a}$, $\tilde{F}_{1b}$), and a type-2 membership function in input x_2 ($\tilde{F}_2$). The rule base of the proposed architecture is composed of two rules (l_1 e l_2), with two antecedents and one consequent each. The size of the rule base increases with the number of membership functions per entry.

$$R^{l1}: IF\ x_1 is\ \tilde{F}_{1a}^{l1}\ and\ x_2\ \ is\ \tilde{F}_2^{l1}, THEN\ y\ is\ \tilde{G}^{l1} \qquad (1)$$
$$R^{l2}: IF\ x_1 is\ \tilde{F}_{1b}^{l2}\ and\ x_2\ \ is\ \tilde{F}_2^{l2}, THEN\ y\ is\ \tilde{G}^{l2} \qquad (2)$$

The membership function of antecedent x_1 is activated by x_1', and produces an upper ($\overline{\mu}_{\tilde{F}_1^l}(x_1')$) and lower ($\underline{\mu}_{\tilde{F}_1^l}(x_1')$) activation degree at x_1'. The activation degrees of antecedent x_2 are obtained in the same way. The t-norm operator $\star$ (minimum) of the upper and lower activation degrees are taken, producing the upper ($\overline{f}$) and lower ($\underline{f}$) activation level, according to equations (3) and (4):

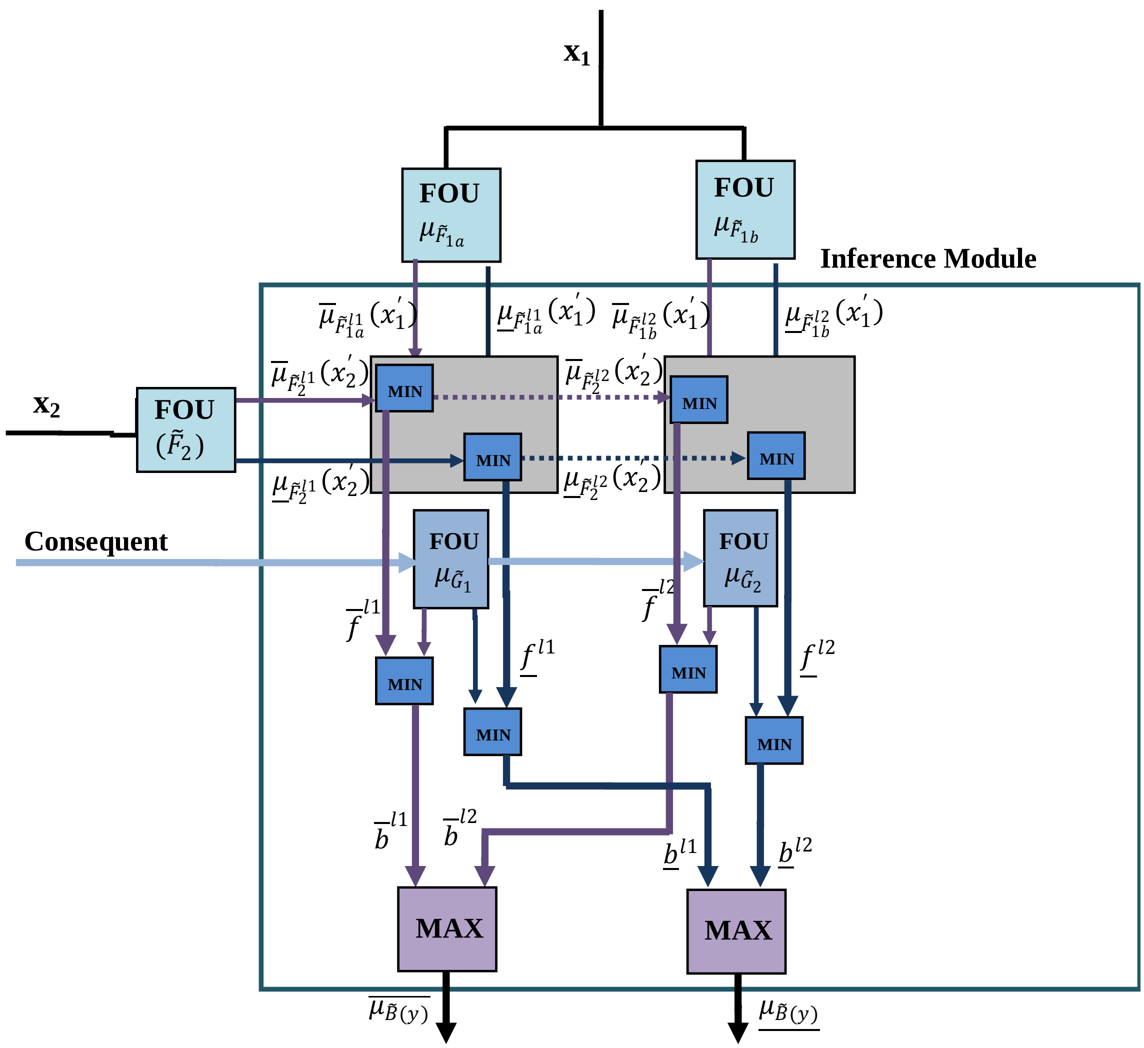

Figure 3. Proposed Architecture of Type-2 Fuzzy Inference System.

$$\underline{f}^l(x') = \underline{\mu}_{\tilde{F}_1^l}(x_1') \star \underline{\mu}_{\tilde{F}_2^l}(x_2') = \min\left[\underline{\mu}_{\tilde{F}_1^l}(x_1'), \underline{\mu}_{\tilde{F}_2^l}(x_2')\right] \qquad (3)$$
$$\overline{f}^l(x') = \overline{\mu}_{\tilde{F}_1^l}(x_1') \star \overline{\mu}_{\tilde{F}_2^l}(x_2') = \min\left[\overline{\mu}_{\tilde{F}_1^l}(x_1'), \overline{\mu}_{\tilde{F}_2^l}(x_2')\right] \qquad (4)$$

Then, the calculation of $\mu_{\tilde{B}}(y)$ is performed by using the t-norm operator ★ (minimum) between the upper degree of activation ($\overline{f}^{l}$), resulting from rule ($\overline{f}^{l}$) and the upper membership function which is consequent of the same rule $\overline{\mu}_{\tilde{G}^l}(y)$, [$\overline{b^l} = \overline{f}^{l} \star \overline{\mu}_{\tilde{G}^l}(y)$], for all $y \in Y$. The calculation of the lower curve is performed in the same way: [$\underline{b^l} = \underline{f}^{l} \star \underline{\mu}_{\tilde{G}^l}(y)$], as equations (5) and (6).

$$\underline{b^l}(x') = \min\left[\underline{f}^{l}, \underline{\mu}_{\tilde{G}^l}(y)\right] \quad (5)$$

$$\overline{b^l}(x') = \min\left[\overline{f}^{l}, \overline{\mu}_{\tilde{G}^l}(y)\right] \quad (6)$$

The resulting function is obtained by using the t-conorm operator ∨ (maximum), represented by equation (7).

$$\mu_{\tilde{B}}(y) = \left[\underline{b^1}(y) \vee \underline{b^2}(y), \overline{b^1}(y) \vee \overline{b^2}(y)\right] \quad (7)$$

The output of the inference system is processed by a type reducer and a defuzzifier circuit to obtain the crisp output.

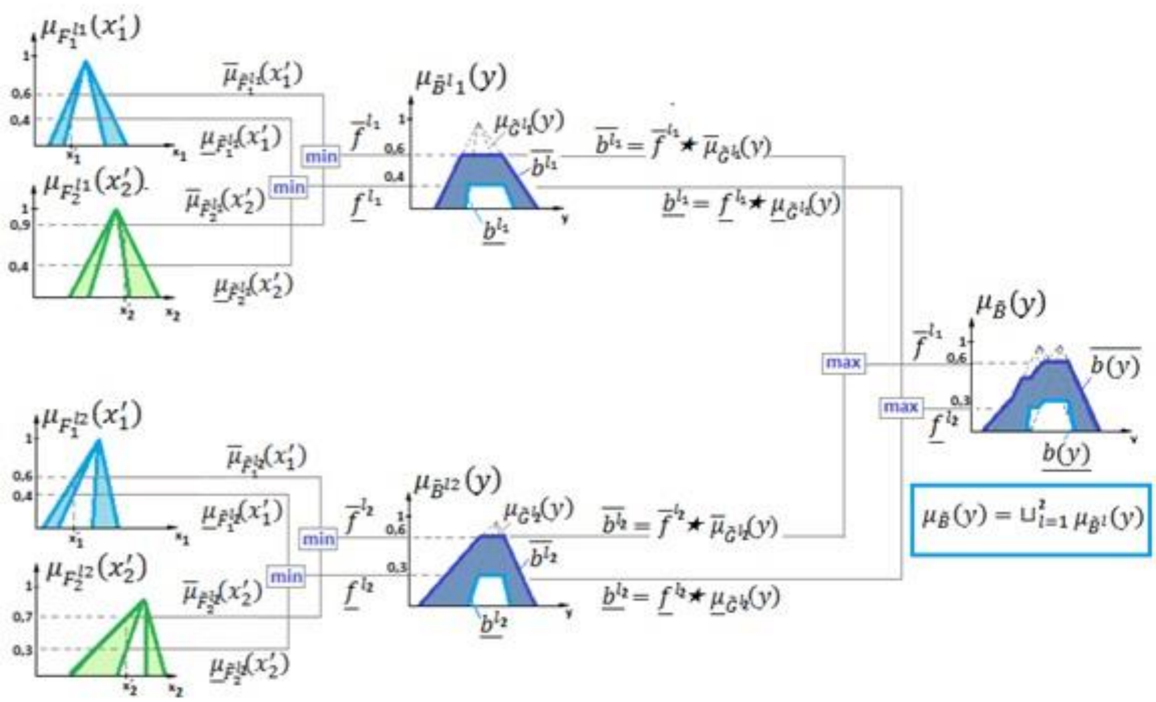

Figure 4. Type-2 Fuzzy Logic Inference for two rules.

A. *Minimum Circuit*

The current-mode minimum circuit (Figure 5) was proposed by Rizol [Rocha Rizol et al, 2010]. This circuit is expressed by bounded-difference, which is a fundamental fuzzy logic function.

$$I_{OUT} = MIN(I_X, I_Y) = I_X \Theta (I_X \Theta I_Y) \quad (8)$$

where: $$I_X \Theta I_Y = \begin{cases} I_X - I_Y & \text{se } I_X > I_Y \\ 0 & \text{se } I_X < I_Y \end{cases}$$

The bounded-difference can be implemented with current mirrors and an MOS transistor connected as diode.

If $I_y > I_x$, current I_x will be drained by transistors M_2 and M_4, therefore the current in both transistors M_5 and M_6 would be null. Then, the output current, I_{out}, is given by I_x.

If $I_x > I_y$, current I_y will be mirrored to transistors M_2 and M_4, and the current in both transistors M_5 and M_6 would be I_x - I_y. Then, output current, I_{out}, is given by I_y; that represents the lowest injected current in the circuit.

The operation of the minimum circuit was simulated using the Mentor Graphics simulator and a 0.35μm AMS model.

The layout and microphotograph of the Min circuit are presented in Figure 6, respectively. Figure 7 shows the simulation result of the minimum circuit. Current I_x is a sinusoidal signal with amplitude of 10μA, DC offset of 10μA and a frequency of 0.1 kHz and I_y varying between [0, 20] μA.

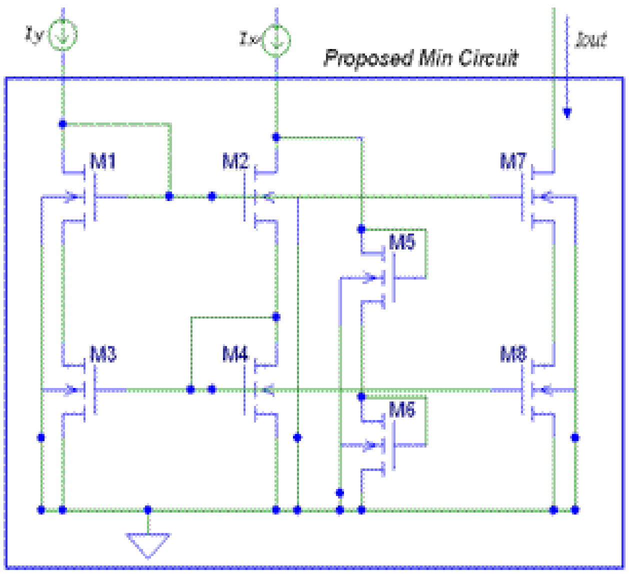

Figure 5. Minimum circuit.

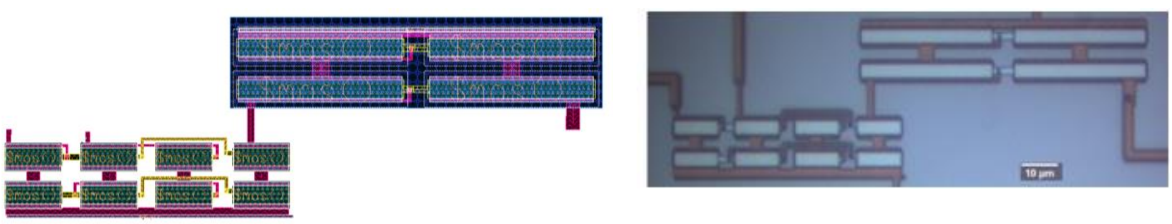

Figure 6. Layout and Microphotograph (500x) of the minimum circuit.

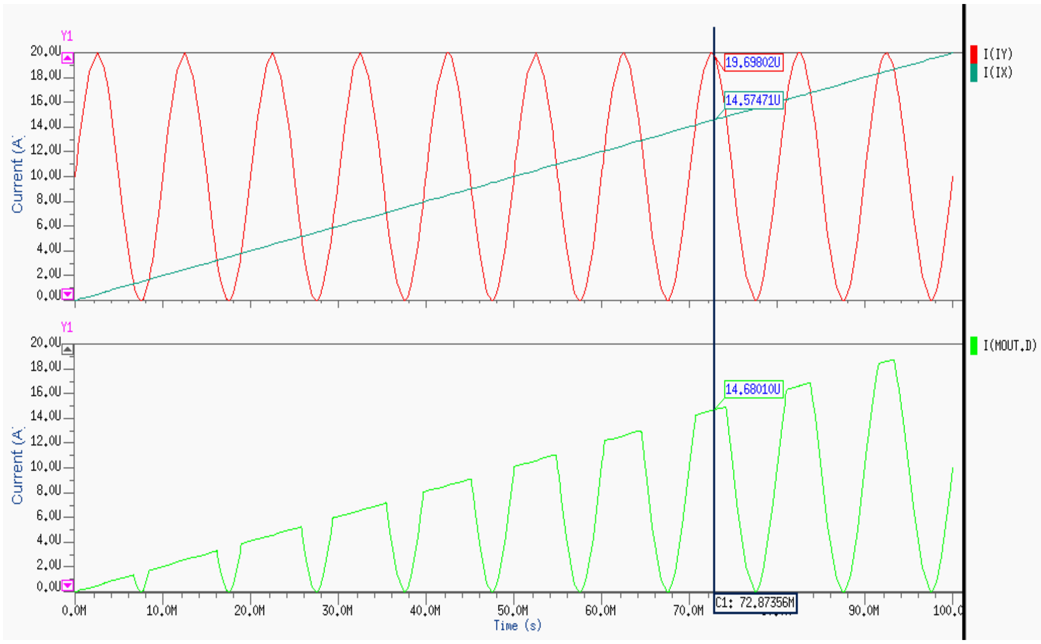

Figure 7. Simulation result of the minimum circuit.

B. Maximum Circuit

The current-mode maximum circuit (Figure 9) was proposed by Yosef [Yosefi et al, 2009]. The operation of this circuit is given by the function shown below:

$$I_{OUT} = MAX(I_X, I_Y) = I_X+(I_X \Theta I_Y) \quad (9)$$

The following is the operation of the circuit:

If $I_y > I_x$, the current flowing through transistor M_6 is given by I_y-I_x and the current passing through transistors M_2 and M_4 is given by: I_y=I_y-I_x+I_x. This current is mirrored to the output.

If $I_x > I_y$, the transistor is cut and the current passing through transistors M_2 and M_4 is given by: I_x. This current is mirrored to the output.

The operation of the maximum circuit was simulated using the Mentor Graphics simulator and the 0.35µm AMS model.

The Max circuit layout and microphotograph are presented in Figure 8, respectively. Figure 10 shows the maximum circuit simulation result. Current I_y is a sinusoidal signal with an amplitude of 10µA, DC offset of 10µA, and a frequency of 0.25 kHz and I_x varying between [0,20] µA.

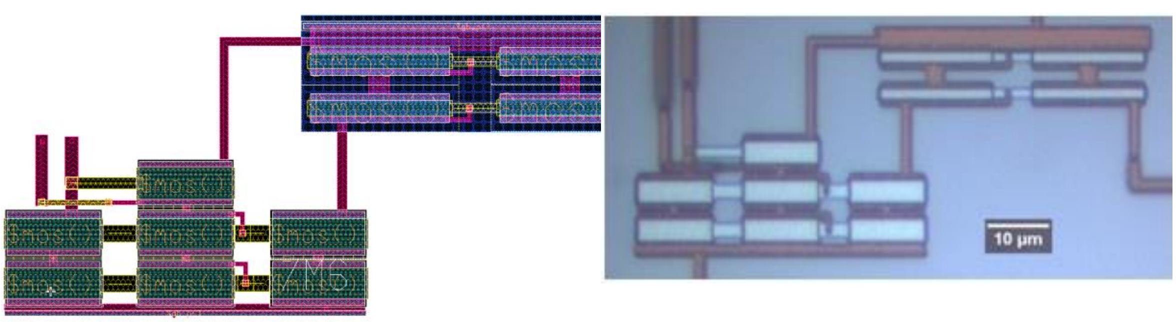

Figure 8. Layout and Microphotograph (500x) of the maximum circuit.

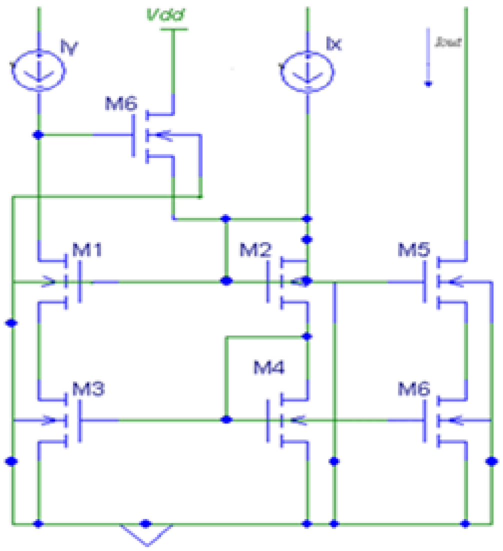

Figure 9. Maximum circuit.

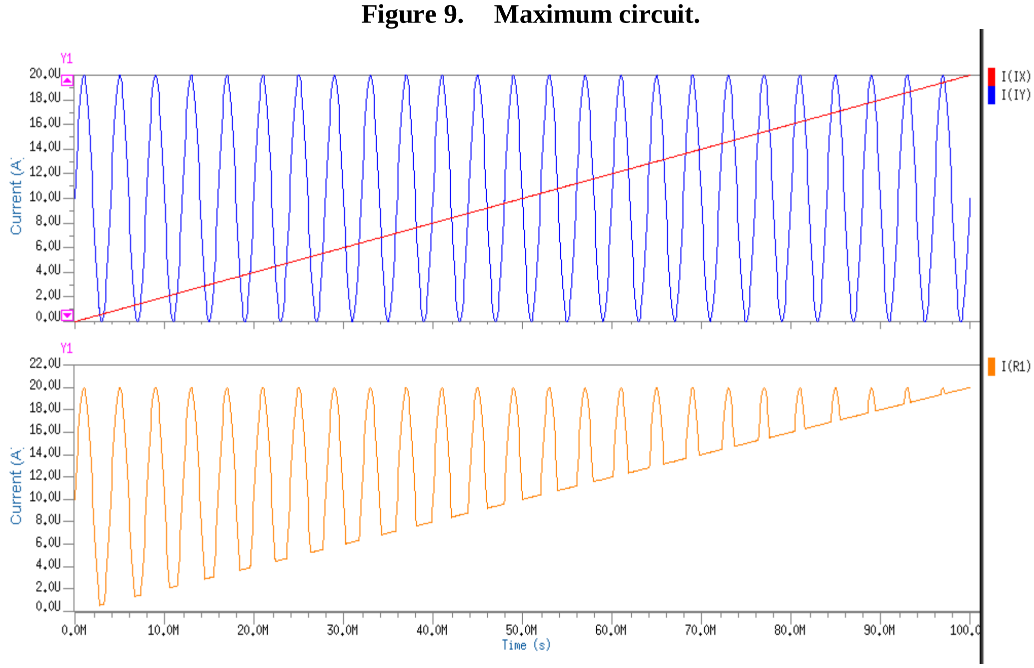

Figure 10. Simulation result of the maximum circuit.

3. SIMULATION RESULTS T2FIS

The proposed circuit of T2FIS (Type-2 Fuzzy Inference System) is part of a type-2 fuzzy controller with two inputs and one output. To illustrate the operation of Mamdani inference system architecture proposed in this paper, it is hereafter presented the Mentor Graphics simulation of the proposed architecture of T2FIS with two membership functions on each input, four rules and three output membership functions (consequent of the rule), using the interval type-2 fuzzy rule base matrix, shown in Figure 11. The rule base size increases with the number of membership functions per input, and it depends on the number of entries in the system. As the circuits proposed in this paper are modular, a T2SIF with a larger number of rules can be obtained using more FOU, minimum and maximum circuits.

The rule base can also be written in the form of conditional rules such as IF-THEN, represented in the form If (antecedent) then (consequent), as shown below:

Rule 1: If X_1 is Z and X_2 is N then output is N.
Rule 2: If X_1 is P and X_2 is N then output is Z.
Rule 3: If X_1 is Z and X_2 is Z then output is Z.
Rule 4: If X_1 is P and X_2 is Z then output is P.

X_2 \ X_1	**Z**	**P**
N	N	Z
Z	Z	P

Figure 11. T2FIS archtecture Rule Base.

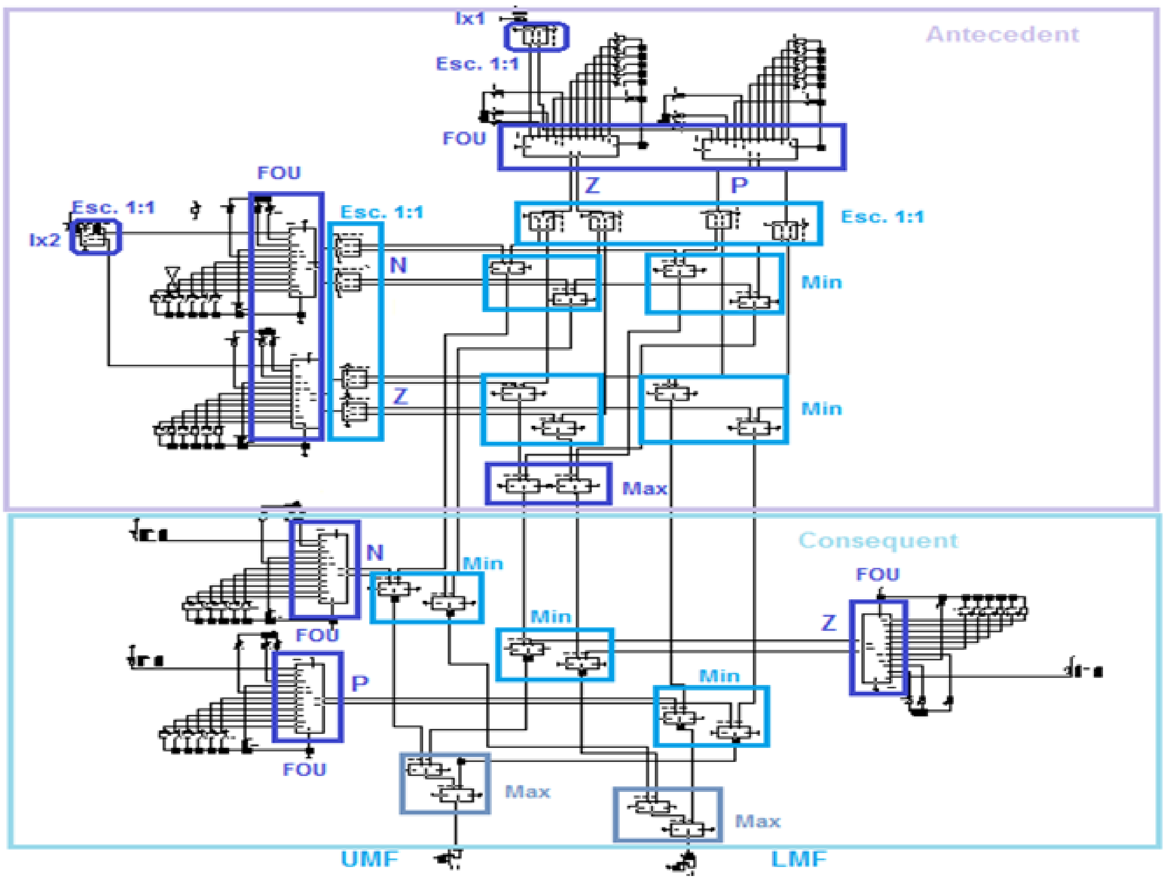

Figure 12. Interval type-2 inference circuit squematic.

Figure 12 shows the schematic diagram of the testing inference circuit. This circuit has two inputs, X_1 and X_2, with two interval type-2 membership functions for each of them. The type-2 fuzzifier circuit, in this work is called FOU circuit, is used to generate interval type-2 membership functions [Rocha Rizol et al, 2011], and the shape and position of membership functions can be programmed.

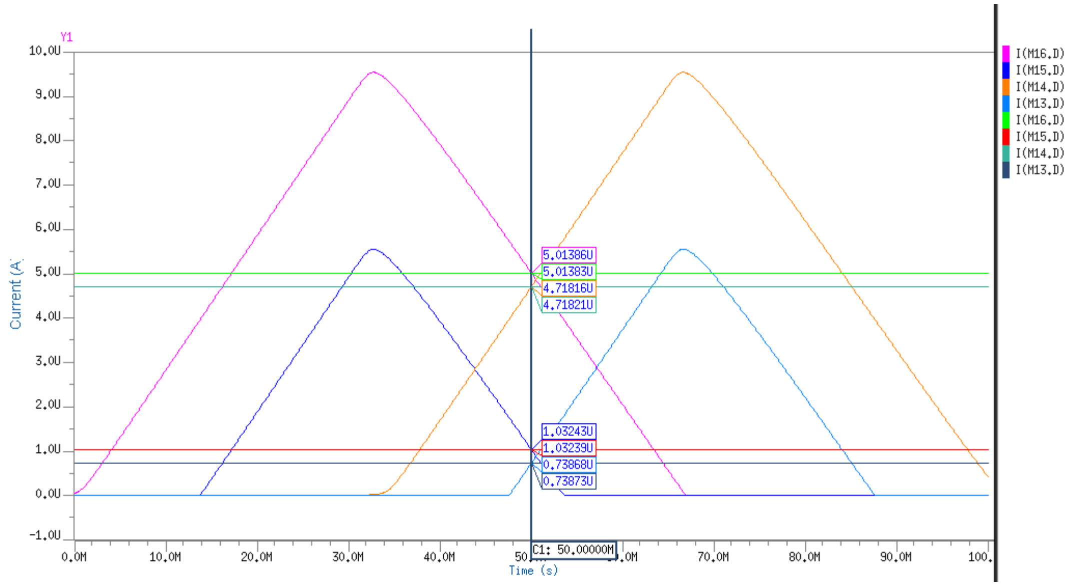

Figure 13. **Type-2 Membership function of input X_1 (Z left and P right).**

Figures 13 and 14 show the input membership functions obtained by programming the FOU circuit [Rocha Rizol et al, 2011].

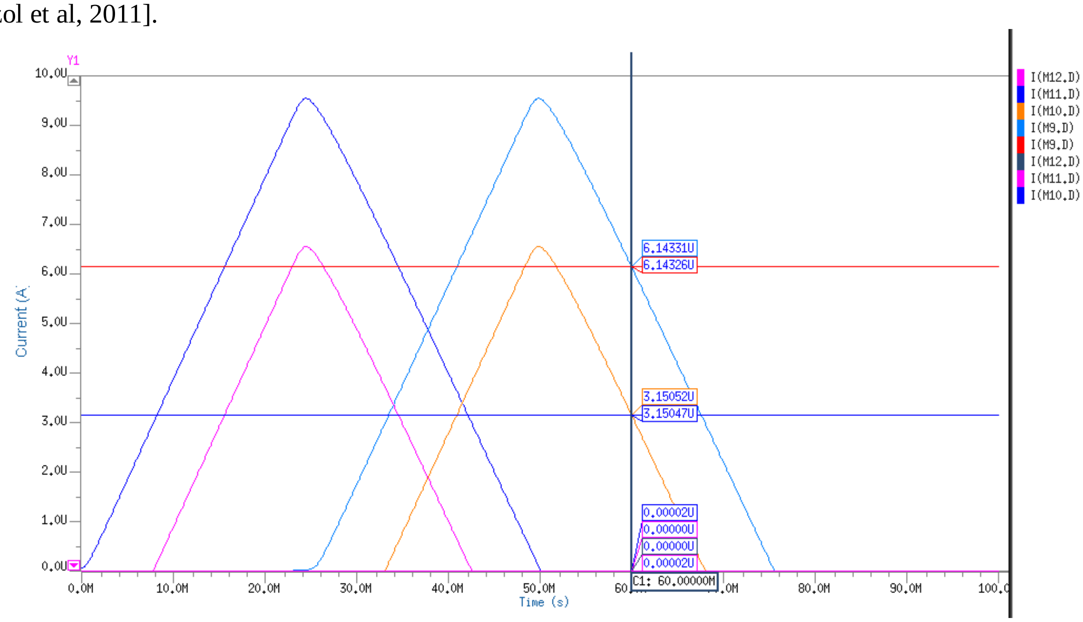

Figure 14. **Type-2 Membership function of input X_2 (Z left and N right).**

For the input current X_1 being equal to 5µA, the interval type-2 fuzzy set Z is activated providing an upper activation degree of 5.01µA and a lower one of 1.03µA, and interval type-2 fuzzy set P is enabled, providing an upper activation degree of 4.71µA, and a lower of 0.71 µA, as shown in Figure 13. For the input current X_2 to equal 6µA (Figure 14), interval type-2 fuzzy set N is also activated, obtaining the upper activation degree of 6.14 µA, and a lower one of 3.15 µA.

Therefore, based on this analysis, input interval type-2 fuzzy sets X_1, P, and Z were enabled. At input X_2, interval type-2 fuzzy set N was activated. Thus, rules 1 and 2 were activated, as shown in Figure 13 (blue). Rule 1, is performed to calculate the minimum between membership functions of upper and lower N and P, as shown in equations (10) (11), and Rule 2 is the calculation of the minimum between membership functions Z and N, as shown in equations (12) and (13). The result of the simulation stage is shown in Figure 15, and it shows that only rules 1 and 2 were active, and also the results of equations (10), (11), (12) and (13), respectively.

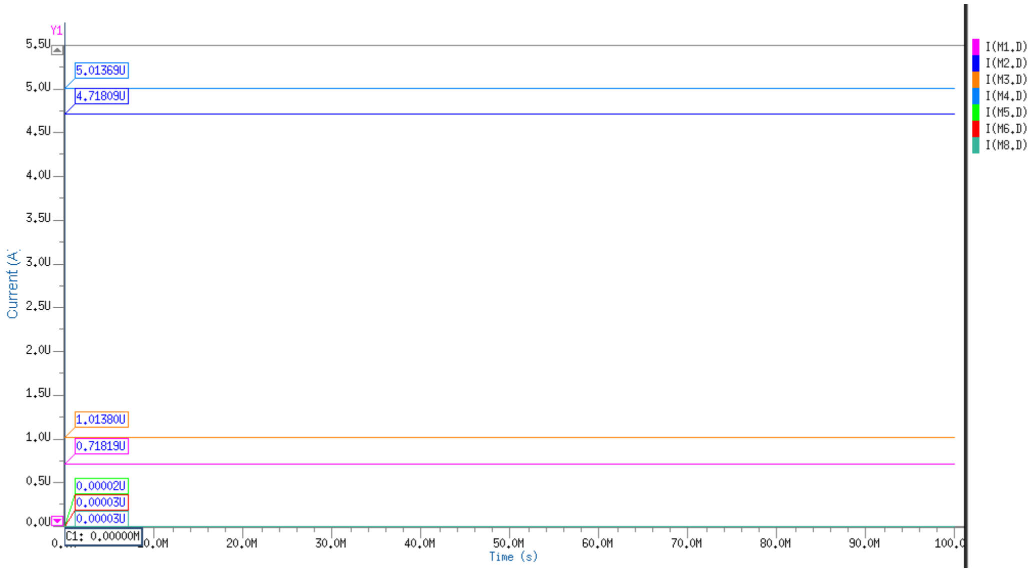

Figure 15. Upper and lower activation degree of the rule base.

$$\underline{f}^{l1}(\mathrm{x}') = \min\left[\underline{\mu}_Z(x_1'), \underline{\mu}_N(x_2')\right] = 0.73\mu\mathrm{A} \tag{10}$$

$$\overline{f}^{l1}(\mathrm{x}') = \min\left[\overline{\mu}_Z(x_1'), \overline{\mu}_N(x_2')\right] = 4.71\mu\mathrm{A} \tag{11}$$

$$\underline{f}^{l2}(\mathrm{x}') = \min\left[\underline{\mu}_P(x_1'), \underline{\mu}_N(x_2')\right] = 1.03\mu\mathrm{A} \tag{12}$$

$$\overline{f}^{l2}(\mathrm{x}') = \min\left[\overline{\mu}_P(x_1'), \overline{\mu}_N(x_2')\right] = 5.01\mu\mathrm{A} \tag{13}$$

The architecture presented in this paper has three consequents (output type-2 membership functions – Figure 16). As shown in Figure 11, rules 2 and 3 have the same consequent. Therefore, it was used a maximum circuit to determine the resulting current of consequent Z.

The next step is to perform the calculation of the minimum of the output membership function (as a consequent of the rule) and the value of the upper and lower degrees of activation, obtained in the previous step. In this simulation, rules 1 and 2 were activated. The rule enables an output membership function N, having a lower degree of activation of $\underline{f}^{l1}(\mathrm{x}') = 0.71$ µA and an upper one of $\overline{f}^{l1}(\mathrm{x}') = 4.71$ µA.

$$\overline{b^{l1}} = \min\left[\overline{f}^{l1}, \overline{\mu}_{\tilde{N}^{l1}}(y)\right] = \min\left[4.71\mu\mathrm{A}, \overline{\mu}_{\tilde{N}^{l1}}(y)\right] \tag{14}$$

$$\underline{b^{l1}} = \min\left[\underline{f}^{l1}, \underline{\mu}_{\tilde{N}^{l1}}(y)\right] = \min\left[0.71\mu\mathrm{A}, \overline{\mu}_{\tilde{N}^{l1}}(y)\right] \tag{15}$$

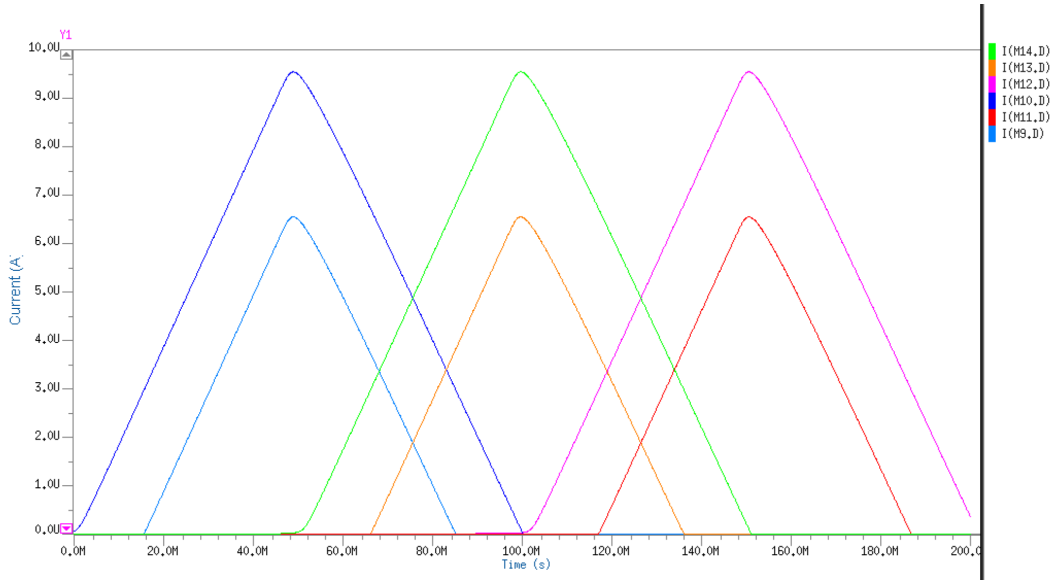

Figure 16. **Type-2 Membership function of output (N left, Z central and P right).**

In turn, the second rule activates output membership function Z, having a lower degree of activation $\underline{f}^{l2}(x')$= 1.03µA and an upper one of $\overline{f}^{l2}(x')$ = 5.01 µA.

$$\overline{b^{l2}} = \min\left[\overline{f}^{l2}, \overline{\mu}_{\tilde{Z}^{l2}}(y)\right] = \min\left[5{,}01\mu A, \overline{\mu}_{\tilde{Z}^{l2}}(y)\right] \tag{16}$$

$$\underline{b^{l2}} = \min\left[\underline{f}^{l2}, \underline{\mu}_{\tilde{Z}^{l2}}(y)\right] = \min\left[1{,}01\mu A, \overline{\mu}_{\tilde{Z}^{l2}}(y)\right] \tag{17}$$

The simulation result of this step is shown in Figure 17. As it can be seen, the resulting N and Z were enabled with the degree of activation presented in equations (14), (15), (16) and (17).

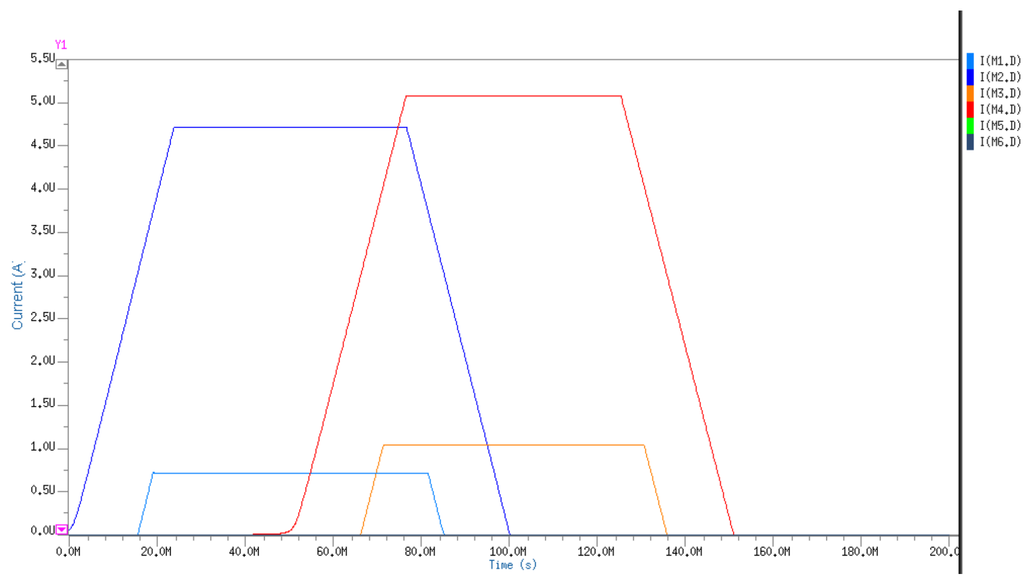

Figure 17. **Simulation results of the minimum between the output membership function and the activation degree (N on the left and Z on the center).**

Finally, the calculation of the upper and lower output membership function is made, using the maximum circuit. The simulation result of this step is shown in Figure 18.

Figure 18. Simulation results of the type-2 inference circuit.

In order to validate interval type-2 fuzzy inference system that uses the rule base shown in Figure 11, it was also simulated in Matlab using the interval type-2 fuzzy toolbox [Castro et al, 2007]. As it can be seen in Figures 19 and 20, for the same input parameters previously used (X_1= 5μA and X_2 = 6μA), rules 1 and 2 were activated (output membership function, Z and N) and type-2 membership function output result is similar to the one obtained in Figure 18, proving the operation of the inference circuit.

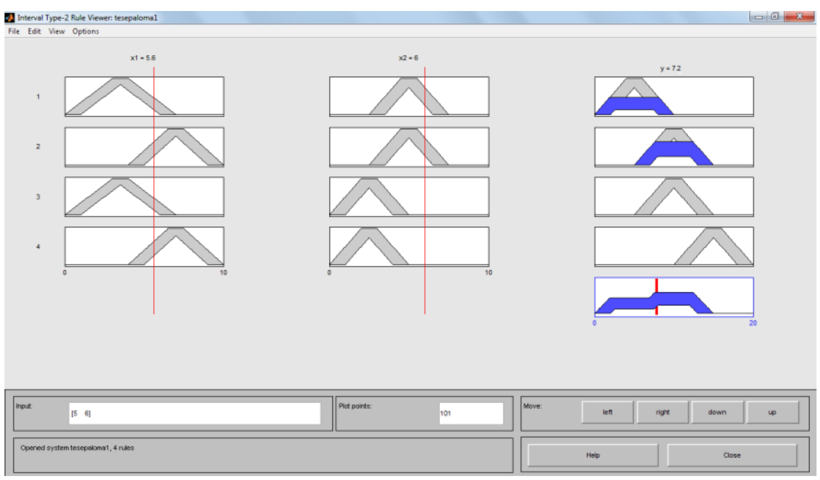

Figure 19. Matlab simulation results of the type-2 inference circuit.

Table I shows the caracteristics of the proposed IT2FIS circuit, and Table II performs a comparation between the proposed IT2FIS circuit and some previous works. The previous works presented in Table II are type-1 fuzzy inference system, because IT2FIS circuits were not found in the literature.

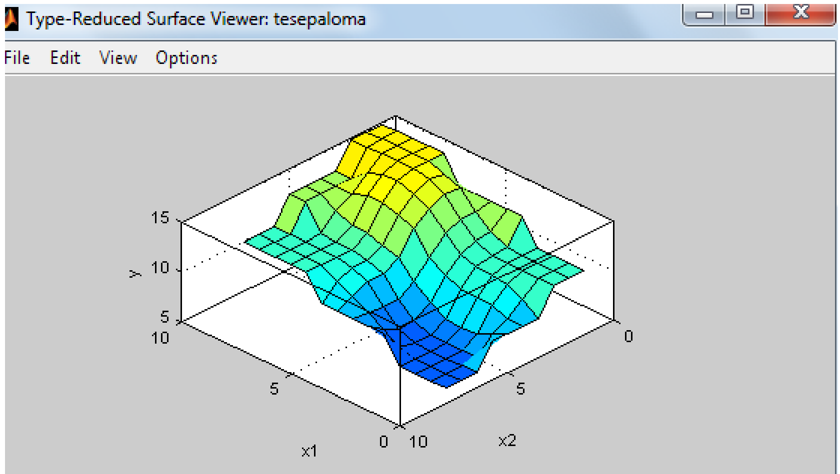

Figure 20. Matlab simulation surface of the type-2 inference circuit.

TABLE I. CHARACTERISTICS OF PROPOSED IT2FIS CIRCUIT

	Description	**Features**
1	Technology	0.35µm CMOS
2	Mode type	Current-mode
3	Power supply	3.3(V)
4	Complexity	Mamdani 4-rule@2-input@1 output

TABLE II. COMPARATION OF PROPOSED MFC CIRCUIT WITH PREVIOUS WORKS.

Ref	**Technology**	**Signal**	**Mode type**	**Suply**	**Complexity**	**Application**
[Yosefi et al, 2011]	0.35µm CMOS	Mixed Signal	Current-mode	3.3(V)	Sugeno 16-rules@2-input@1 output	FLC
[Amirkhanzadeh, 2005]	0.35µm CMOS	Mixed Signal	Current-mode	3.3(V)	Mamdani 9-rules@2-input@1 output	FLC
This work	0.35µm CMOS	Analog	Current-mode	3.3(V)	Mamdani 4-rule@2-input@1 output	Type-2 FLC

4. CONCLUSION

This paper proposes a new architecture for an analog implementation of Mamdani Type-2 Fuzzy Inference Systems, which is the inference part of the Interval Type-2 Fuzzy Logic Controller (IT2FLC) chip.
Through the obtained circuit simulation results, in the AMS CMOS 0.35µm technology, it can be observed that the architecture of IT2FIS works properly, when compared to the simulation result of the same IT2FIS in the Interval Type-2 Fuzzy Logic Toolbox of Matlab software. The proposed architecture is composed of current mode Min and Max circuits and can be very useful as Mamdani type-2 fuzzy inference system circuit in type-2 fuzzy controller.

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