A Novel Reconfigurable Membership Function Circuit for Analog Fuzzy Logic Controller

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***Abstract*—A novel reconfigurable membership function circuit (RMFC) for analog fuzzy logic controller (FLC) is presented. The reconfigurable characteristic makes it more suitable in industrial control applications when compared with the MFC proposed in [1]. By proper signal arrangement, the RMFC can re-sample the same input current in different configuration, which reduces the number of MFC in analog FLC. Thus, the power consumption and circuitry are smaller than the MFC proposed in [2]. The full current mode circuitry ensures a low power supply voltage and high speed. The analog input signal is processed directly without any need of an A/D or D/A interface. SPECTRE simulation results validate the feasibility of the proposed RMFC that is implemented in 0.35-µm CMOS with a battery of 1.5-V supply.**

***Key Words*--Fuzzy logic controller (FLC), Membership function circuit (MFC), low voltage, current mode.**

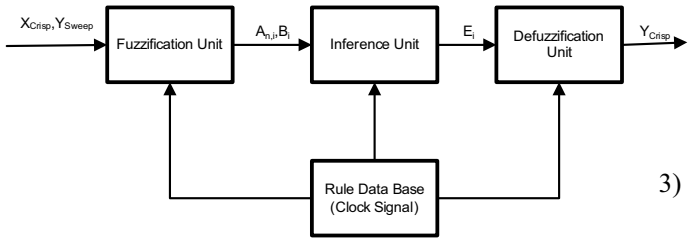
Introduction

Fuzzy logic is designed to mimic the human thinking process by incorporating the uncertainty inherent to all physical systems [3]. Relying on the human nature of the fuzzy logic, an increasing number of successful applications have been developed, such as automatic process control, pattern-recognition systems, fuzzy neurons, chaos, etc. Rapid developments in semiconductor, computing, and communication technologies turned portable devices such as personal digital assistants and laptops with wireless connectivity in powerful and ubiquitous equipments. Moreover, a new generation of sensors called “smart” sensors consists of three basic elements; a physical transducer, a controller/ memory core and a network interface [4]. The physical transducer senses the physical quantity and converts it to an electrical signal. The signal is fed to an A/D converter to produce a digital value for use by the controller. On the other hand, the analog to digital (A/D) converter circuit or the (D/A) occupies a considerable amount of resources in a portable device. Smart sensors or portable devices equipped with analog FLC have a bright future because their compatibility with the analog fuzzy world is higher. Moreover, analog FLC usually presents better performance than digital implementations in real-time control systems when speed is a concern. Also, current mode circuits exhibit a good potential since using current as a signal carrier implies no restrictions from the supply voltage. Moreover, simple current basic building blocks easily fulfil a small circuitry requirement, as well as high speed.

This paper presents a novel reconfigurable membership function circuit for switched-current mode analog FLC. Its reconfigurable characteristics and low supply voltage are attractive for portable devices and smart sensors.

Fuzzification strategies

A FLC consists of four fundamental units: fuzzification unit, inference unit, defuzzification unit and rule base unit as shown in figure 1.



Figire 1 FLC architecture block diagram.

The fuzzification unit provides a fuzzy partition of the input and output universes of discourse of the different variables as well as a choice of the membership function which describes each fuzzy set. Concerning the input variables, the fuzzification operation is performed by circuits known as membership function circuits (MFC's). Several classes of parameterized functions are used to define membership functions: triangles and trapezoids are popular in industrial control applications due to their simplicity while Gaussian, sigmoidal, or bell-shaped functions are especially used in adaptive neuro-fuzzy controllers [5]. Membership functions can be reconfigured as S-shapes, Z-shapes, triangles and trapezoids is the design goal since they are so popular in industrial control applications and can be easily implemented by current mode CMOS circuits.

To understand the mathematical operations involved in an MFC, let us discuss three strategies to generate symmetric trapezoidal functions illustrated in figure 2.

1) The fuzzifier operation shown in figure 2(a) is carried out as follows:

$$fuzzy\ (x) = x_{ref}\,\Theta[m(x\Theta x_2) + m(x_1\Theta x)] \quad (1)$$

where Θ is a rectification or bounded difference operator defined as:

$$a\Theta b = \begin{cases} a-b & if\ a > b \\ 0 & otherwise \end{cases} \quad (2)$$

Current-mode realizations that implement this operation have been proposed in [6].

2) The technique illustrated in figure 2(b) performs the following transformation:

$$fuzzy(x) = m(x\Theta x_1) - m(x\Theta x_2) - m(x\Theta x_3) \quad (3)$$

The current-mode circuit used in [7] follows this technique.

3) The strategy proposed by the authors in [8] employs the parameters depicted in figure 2(c). It realizes the following transformation:

$$\begin{aligned} fuzzy(x) &= x_{ref}\Theta m[(x\Theta x_{auz}) + m(x_{aux}\Theta x)\Theta x_{sat}] \\ &= x_{ref}\Theta m(|x - x_{aux}|\,\Theta x_{sat}) \end{aligned} \quad (4)$$

In any case, the basic mathematical operations required are addition(+), subtraction(-), rectification(⊙), and scaling(m).

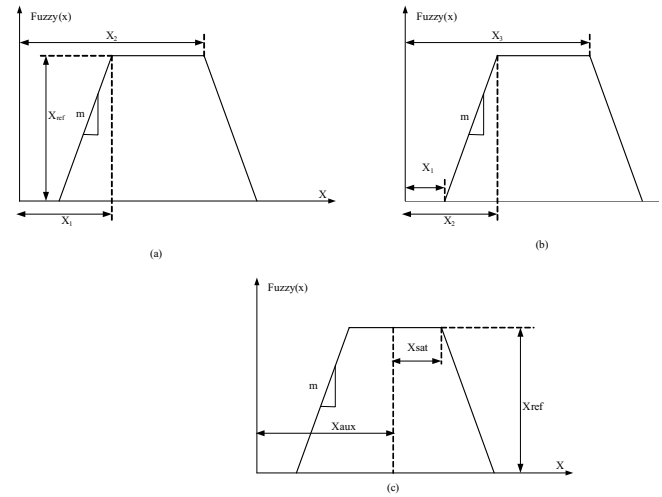


Figure 2 Strategies to generate membership functions

The strategy of the proposed RMFC in this paper is based on strategy c, which is carried out as equation 4 and illustrated in figure 2(c). Since there is no need of duplicating the input current as the circuit proposed in [9], the power consumption will be lowered.

circuit implementation

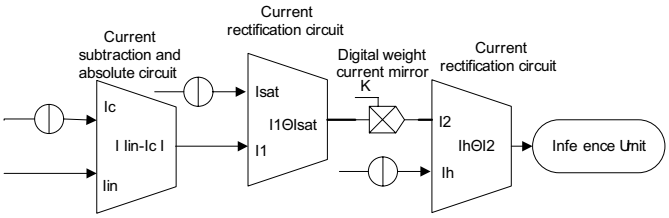


Figure 3 Block diagram of the proposed RMFC.

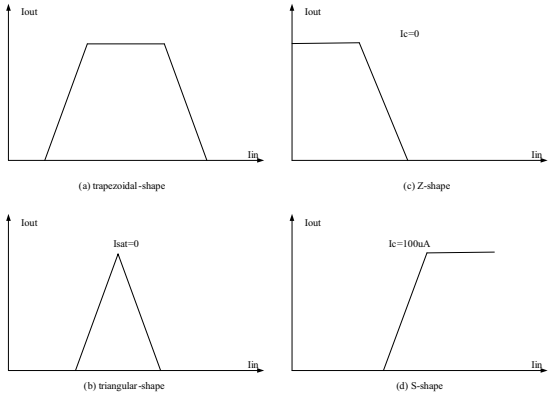


Figure 4 Different kind of transfer function.

Figure 3 shows the block diagram of the proposed RMFC Its input-output characteristic can be assigned by external signals such as Ic, Isat, Ih, and k as illustrated in figure 4. Ic is the middle point of the membership function while Isat is the width of the shoulder. When Isat is zero, a triangular-shape is formed as shown in figure 4(b). Similarly, a Z-shape is formed when Ic is zero and a S-shape is formed when Ic is the maximum value in the universe of discourse, which are shown in figure 4(c) and (d). K is the slope of the membership function and Ih is the maximum output current. Therefore the shape of the membership function can be fine tuned independently by external signals. Similar MFCs have been reported but some of them are either fixed parameters or poor in adjustment and the others are incompatible of low supply voltage.

The following full current mode circuits consist of the proposed RMFC circuit. They are self-biased wide swing SI memory cell, low voltage and high performance current rectification circuit, current absolute subtraction circuit and wide swing cascode digital weight current mirror.

(A) Self bias wide swing SI memory cell

The basic cell in the proposed circuit would be the SI memory cell. In SI circuits, using current as the signal carrier imposes that the impedance at every node is low. The settling time of a SI memory cell, with the structure shown in figure 5, is determined by the time constant given by

$$\tau = \frac{C}{g_{m0}} \quad (5)$$

where C is the total capacitance at the gate of the memory transistor M0 and g_{m0} is the trans-conductance of the same transistor. The simplest way to raise g_m is to increase the W/L ratio of the MOSFET. However, since the total capacitance will also be increased simultaneously, it would be necessary to use a cascode transistor in the output MOSFET avoiding a heavy increase in the capacitance, at the sacrifice of voltage headroom. So, a self-bias wide swing current mirror is proposed in the thesis as illustrated in figure 6 to lower the signal distortion and supply voltage.

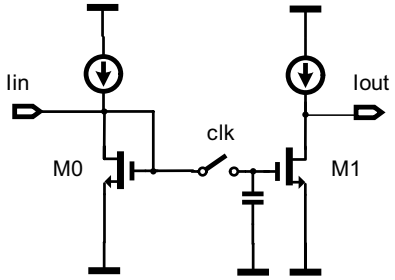


Figure 5 First generation SI memory cell.

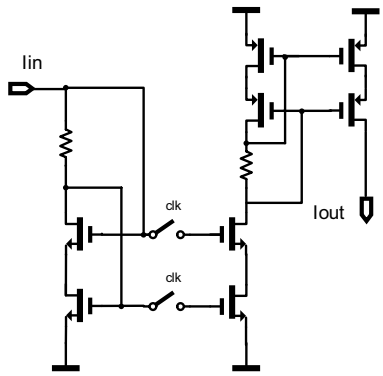


Figure 6 Self-bias wide swing SI memory cell

(B) Low voltage, high performance current rectification circuit

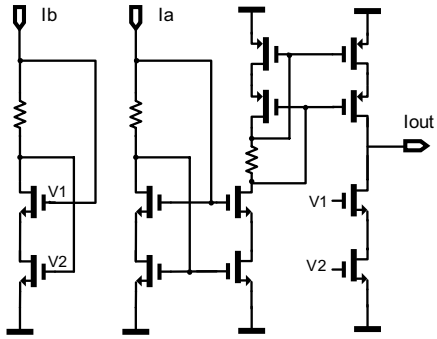


Figure 7 Low voltage, high performance current rectification circuit

The current rectification circuit realizes equation (2) is based on the circuit mentioned in [10]. Figure 7 shows a highly linear current subtraction circuit with low voltage supply requirements. It is used to obtain the subtraction of Ia and Ib at a high swing, high impedance output node. The circuit consists of three self bias wide swing cascode current mirrors, which reduces voltage and current biasing requirements and raise the precision in current rectification circuit.

(C) Current absolute subtraction circuit

The proposed absolute subtraction circuit, which is shown in figure 8, consists of a current rectification circuit as mentioned above, and a high-speed current comparator. The absolute subtraction circuit gives the absolute difference between Ia and Ib. Mn1 and Mp2 work as the source follower. Mn2 and Mp2 work as the current comparator. When Ia>Ib, V is logic low and Mp1 is on. The difference current between Ia and Ib flows through Mp1 to output node. When Ia<Ib, V is logic high and Mn1 is on. The difference current between Ia and Ib flows through Mp3 and Mp4. Since Mp3 and Mp4 are self biased, Mp5 and Mp6 mirror this difference current. Thus making the output current equals the absolute difference value between Ia and Ib.

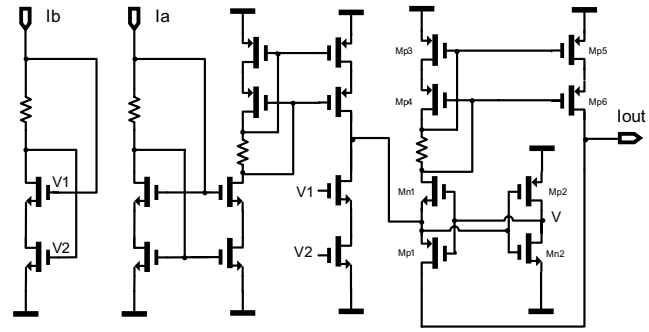


Figure 8 Current absolute subtraction circuit.

(D) Wide swing cascode digital weight current mirror

The precision of current mirror is affected by g_m, a practical way to enlarge the g_m is to cascode a MOSFET in wide swing structure avoiding large voltage headroom. Figure 9 is a self bias wide swing cascode digital weight current mirror, which can achieve high precision under low voltage supply and high speed performance.

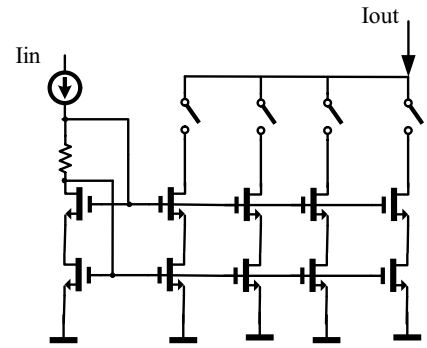


Figure 9 Wide swing cascode digital weight current mirror.

Simulation of the reconfigurable membership function circuit

The analog cells mentioned above compose the proposed RMFC circuit as illustrated in figure 3 and the overall circuit implementation was achieved by using a 0.35-μm CMOS technology with a 1.5-V supply. The universe of discourse is 100μA and the full grade of membership can be set to as large as 100μA. In consideration of speed, a bias current of 50μA is added.

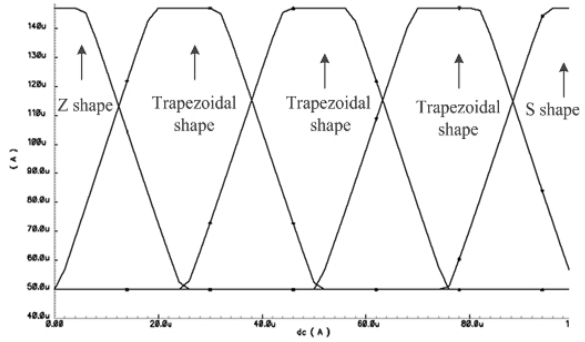


Figure 10 Shapes generated by the proposed RMFB

Figure 10 shows different shapes, such as S-shape, Z-shape and trapezoidal-shape, generated by the proposed RMFB with different Ic. The other parameters such as Isat, Ih and K can also be tuned independently, thus giving the RMFC circuit a wide range of application. Figure 11(a) shows the transient response of the proposed RMFB with parameters listed in table 1. Figure 11(b) is the DC response with the same parameters. The ideal output is 125μA with 45μA input current and the practical output is 124μA after 100ns. As a result, the clock cycle of 100ns is large enough to get the fuzzy value with 98% accuracy in the phase of antecedent fuzzification.

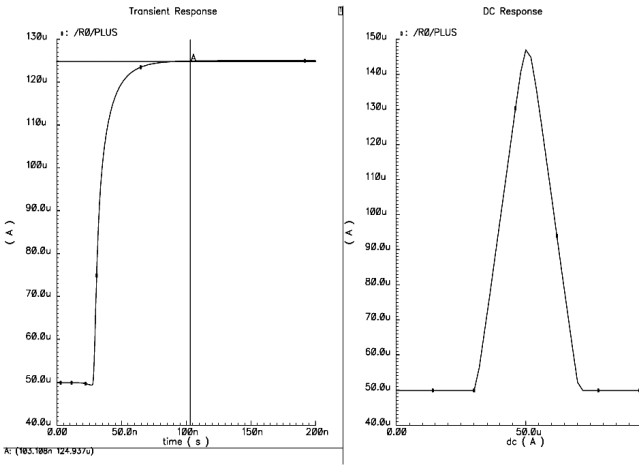


Figure 11 (a) Transient response of the RMFB. (b) DC response of the RMFB.

Ic	Isat	k	Ih	Ibias	I
50μA	0	5	100μA	50μA	45μA

Table 1 Parameters of a triangular shape

Conclusions

A novel RMFC for a fuzzy logic controller has been proposed. The reconfigurable and current mode architecture turns it suitable for portable devices and smart sensor, i.e., exhibiting simpler circuit complexity and lower power consumption. Implemented in 0.35-μm CMOS technology with a 1.5-V supply, the circuit performance was verified with SPECTRE achieving a high speed operation of 10MHz. The achieved accuracy is 98% satisfactorily fulfilling the requirement of most fuzzy logic systems.

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References

[1] O.Arellano-Cardenas, J.A. Moreno-Cádenas, F.Gómez-Castañeda, L. M. Flores-Nava, “CMOS Cells with Continuously Adjustable Parameters for

Implementation of Fuzzy and Neurofuzzy Systems", IEEE 05EX1097 2005, 378-381

[2] Faizal A. Samman, Rhiza S. Sadjad, and Eniman Y. Syansuddin, "The reconfigurable membership function circuit using analog bipolar electronics", IEEE 2002, 537~540.

[3] L.A. Zadeh, "Fuzzy Sets," in *Information and Control.* New York: Academic Press, vol. 8, pp. 338-353, 1965

[4] Yong Zhang; Yikang Gu; Vlatkovic, V.; Xiaojuan, Wang; "Progress of smart sensor and smart sensor networks", Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on Volume 4, 15-19 June 2004 Page(s):3600 – 3606

[5] Iluminada Baturone, Santiago Sánchez-Solano, Ángel Barriga, José L. Huertas, "Implementation of CMOS Fuzzy Controllers as Mixed-Signal Integrated Circuits", IEEE Transactions on FUZZY SYSTEM vol.5, NO.1,February 1997, 1~18

[6] Laurent Lemaitre, Marek Patyra, Soft-Computing Approach to the Design of Current Mirror Circuits, IEEE 1995, 2003~2006

[7] T. Kettner, C. Heite, and K. Schumacher, "Analog CMOS realization of fuzzy logic membership functions," *IEEE J. Solid-State Circ.*, vol. 28,pp. 857–861, July 1993.

[8] J. L. Hrertas, S. Sanchez-Solano, A. Barriga and I. Baturone, "A Fuzzy Controller Using Switched-Capacitor Techniques," in *Proc. Second IEEE International Conference on Fuzzy Systems* vol. 1, pp.516-520, Mar. 1993.

[9] Ngai Kong, Seng-Pan U and R.P. Martins "A Novel Current-Mode Reconfigurable Membership Function Circuit for Mixed-Signal Fuzzy Hardware" in the fourth Regional Inter-University Postgraduate Electrical and Electronics Engineering Conference *(RIUPEEEC 2006), July.2006*.

[10] H. Traff, "Novel approach to high speed CMOS current comparators"

in *Electronics Letters*, Vol.28 , No.3, pp.310-311, 30th January 1992