Fuzzy-based Circuit Partitioning in Built-in Current Testing

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Abstract-- Partitioning a digital circuit into modules before implementing on a single chip is key to balancing between test cost and test correctness of built-in current testing (BICT). Most partitioning methods use statistic analysis to find the threshold value and then to determine the size of a module. These methods are rigid and inflexible since IDDQ testing requires the measurement of an analog quantity rather than a digital signal. In this paper, we propose a *fuzzy-based* approach which provides a soft threshold to determine the module size for BICT partitioning. Evaluation results show that our design approach indeed provides a feasible way to exploit the design space of BICT partitioning.

1. Introduction

In BICT, the module size is limited by the quiescent current value in a fault-free circuit [1-8]. Several papers [3, 6] have contributed to the circuit partitioning. Most of these approaches use a fixed threshold to determine the boundary between normal and abnormal IDDQ. Based on the fixed threshold, the maximum size of a module is decided. However, these methods are rigid since IDDQ testing requires the measurement of an analog quantity rather than a digital signal in the case of voltage testing. In addition, many factors such as temperature and pressure affect the measurement of IDDQ and will make the current drifting. So, it is hard to obtain a threshold exactly. Unlike those fixed threshold methods which use the smallest current as a symptom of defects to limit the module size of a circuit under partitioning, we propose a fuzzy-based approach to decide the module size in BICT partitioning. Our approach is motivated by the observation of imprecise property of IDDQ measurement. We want to provide a robust mathematical framework to deal with the real-world imprecision and uncertainty of IDDQ measurement. We use five parameters, *resolution*, *noise immunity*, *area overhead*, *performance*, and *testing time*, which can be characterized by the module size, and are the input variables of our fuzzy system.

2. Preliminaries

Fig. 1 shows the block diagram of the fuzzy system. Initially, the *mapping function* maps an initial module size to *input variables* (parameters). The input variables are then fuzzified. Based on the fuzzified variables and fuzzy rules, a module size state is determined by the *module size decision logic*. The module size state is expressed by three level of linguistic terms, *small*, *medium*, and *big*. As soon as the module size state is determined, the *module size adjustment logic* adjusts the module size by adding transistors, decreasing transistors, or leaving alone. Since the inference result from the modules size adjustment logic is a fuzzy set, a *defuzzification unit* is used to convert it into a crisp value. The *partition control system* then takes the crisp value to guide the physical partitioning or initiates another iteration. In Fig. 1, those units below the dash line are not part of the fuzzy system and are not in the scope of this paper.

3. Design approach

In this section we will detail the individual steps to carry out our fuzzy system.

3.1 Design of Fuzzy Membership Functions

There are three sets of membership functions in our design: the input variables (including resolution, area overhead, noise immunity, performance, and testing time) membership functions, module size state membership function, and module size adjustment membership function. Fig. 2 shows the three sets of membership functions. Fig. 2(a) shows a sinusoidal shape membership function which is used to

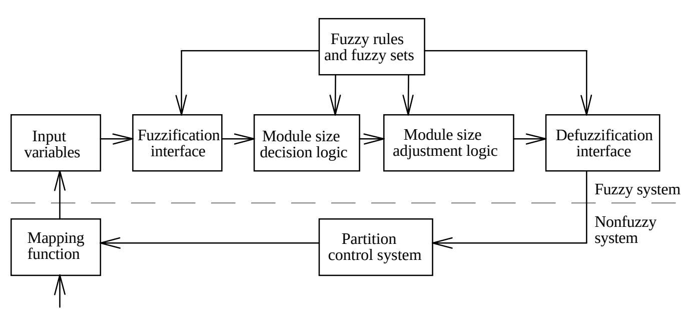

Fig. 1. Block diagram of our fuzzy system.

ASP-DAC '97
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specify an input variable. We use the three linguistic terms *small*, *medium*, and *big* to describe the possible states of an input variable. A general equation to represent the sinusoidal shape membership function is shown as follows [9]:

$$\mu(X) = \left|\sin\left[a - b\left(\frac{X-c}{d}\right)\right]\right|,\ u < X < w \tag{1}$$

where $\mu(X)$ is the membership value for an input variable which can be resolution, area overhead, noise immunity, performance, or testing time; and a, b, c, d, u, and w are constants given in Table 1 for different input variables. The fuzzy variable used in the module size state, as shown in Fig. 2(b), is specified by a trapezoidal shape membership function. There are three linguistic terms labeled *small*, *medium*, and *big* to describe the possible module size state. A general equation to represent the trapezoid shape membership function is given in the following [9]:

$$\mu(Y) = mY + n,\ p < Y < q \tag{2}$$

where $\mu(Y)$is the membership value for the module size state and m, n, p, and q are constants for different fuzzy sets, as shown in Table 2. A triangular shape membership function for the module size adjustment is shown in Fig. 2(c). We use three linguistic terms labeled *increasing transistors*, *leaving alone*, and *decreasing transistors* to describe the possible states of the module size adjustment. A general equation to represent the triangular shape membership function is given in the following [9]:

$$\mu(Z) = rZ + s,\ i < Z < j \tag{3}$$

where $\mu(Z)$ is the membership value for the module size adjustment; and r, s, i, and j are constants for different fuzzy sets, as shown in Table 3.

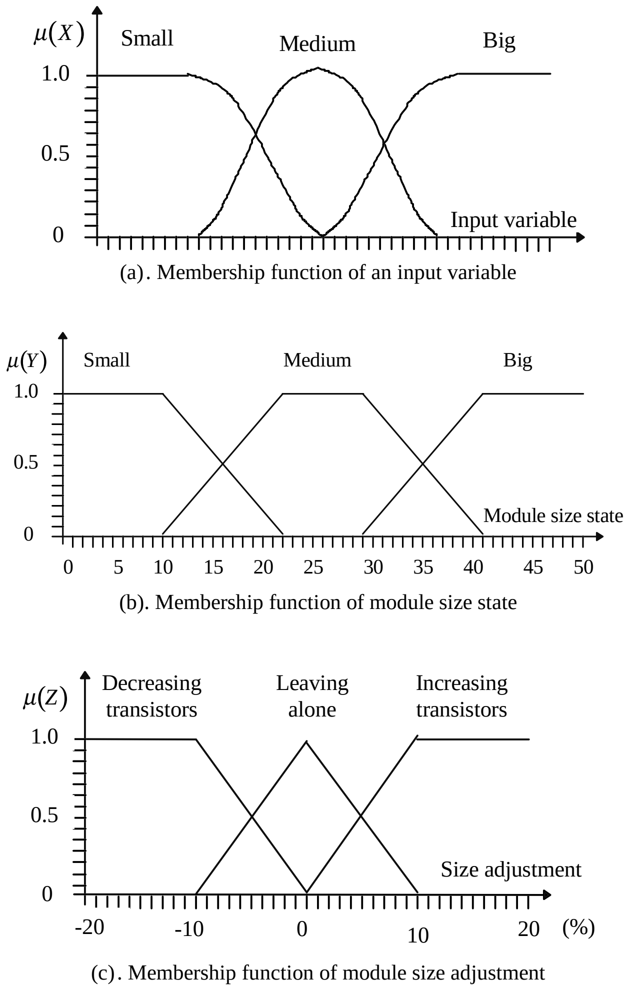


Fig. 2. Membership functions for the fuzzy module size decision system.

3.2 Design of Fuzzy Rules for Module Size State

The number of fuzzy rules is related to the number of fuzzy sets for each input variable. In our fuzzy system, there are five input variables. Each of the five input variables is classified into three levels of fuzzy sets. Therefore, the maximum number of possible rules for the fuzzy system is $3^5 = 243$. It is not always necessary to take the entire space of possible rules into account. For example, no rule is specified for the case of big resolution and small area overhead. We

TABLE 1
CONTENTS OF MEMBERSHIP FUNCTIONS FOR INPUT VARIABLES

Linguistic terms	Quadrant constants		Resolution		Area overhead		Noise immunity		Performance		Testing time	
			c=25	*d=50*	*c=25*	*d=50*	*c=25*	*d=50*	*c=25*	*d=50*	*c=25*	*d=50*
	a	*b*	*u*	*w*	*u*	*w*	*u*	*w*	*u*	*w*	*u*	*w*
Small	$\pi/2$	0	0	25	0	25	0	25	0	25	0	25
	$\pi/2$	1	25	50	25	50	25	50	25	50	25	50
Medium	0	– 1	25	75	25	75	25	75	25	75	25	75
Big	$\pi/2$	1	50	75	50	75	50	75	50	75	50	75
	$\pi/2$	0	75	100	75	100	75	100	75	100	75	100

TABLE 2
CONTANTS OF MEMBERSHIP FUNCTION FOR MODULE SIZE STATE

	m	*n*	*p*	*q*
Small	0	1	0	10
	- 0.084	1.84	10	22
Medium	0.084	- 0.84	10	22
	0	1	22	30
	- 0.084	3.5	30	42
Big	0.084	- 2.5	30	42
	0	1	42	50

TABLE 3
CONTANTS OF MEMBERSHIP FUNCTION FOR MODULE SIZE ADJUSTMENT

	r	*s*	*i*	*j*
Decreasing transistors	0	1	- 0.2	- 0.1
	- 10	0	- 0.1	0
Leaving alone	10	1	- 0.1	0
	- 10	1	0	0.1
Increasing transistors	10	0	0	0.1
	0	1	0.1	0.2

list 63 possible combinations of input values to form 63 fuzzy rules. Each list rule is expressed in “if-then” form. For instance, rule (1) and rule (18) is listed as follows:

rule 1: IF resolution is *big* and area overhead is *big* and noise immunity is *small* and performance is *big* and testing timing is *small* THEN module size state is *small*.

rule 18: IF resolution is *medium* and area overhead is *medium* and noise immunity is *small* and performance is *medium* and testing timing is *medium* THEN module size state is *medium*.

The 63 rules will cover all possible reasonable situations for the modules size state determination.

3.3 Fuzzy Inference for Module Size State and Module Size Adjustment

In this section, we give an example to illustrate how the module size state and module size adjustment is inferred by using input variables as well as fuzzy rules. Assume that the initial module size of a circuit under partitioning is 5000 transistors and the corresponding input variables are R = 32 (nA), A = 37 (μm^2), N = 60 (pF), P = 45 (mHz), and T = 67 (ns). These input variables are first transformed into fuzzy sets by using equation (1) and Table 1. The membership value for each input variable is shown as follows:

$$\mu(R)_{small} = \left|\sin\left(\frac{\pi}{2} - \frac{7}{50}\pi\right)\right| = 0.90, \quad \mu(R)_{medium} = \left|\sin\left(\frac{7}{50}\pi\right)\right| = 0.43$$

$$\mu(A)_{small} = \left|\sin\left(\frac{12}{50}\pi\right)\right| = 0.73, \quad \mu(A)_{medium} = \left|\sin\left(\frac{12}{50}\pi\right)\right| = 0.68$$

$$\mu(N)_{medium} = \left|\sin\left(\frac{35}{50}\pi\right)\right| = 0.81, \quad \mu(N)_{big} = \left|\sin\left(\frac{\pi}{2} - \frac{35}{50}\pi\right)\right| = 0.59$$

$$\mu(P)_{small} = \left|\sin\left(\frac{\pi}{2} - \frac{20}{50}\pi\right)\right| = 0.31, \quad \mu(P)_{small} = \left|\sin\left(\frac{20}{50}\pi\right)\right| = 0.95$$

$$\mu(T)_{medium} = \left|\sin\left(\frac{42}{50}\pi\right)\right| = 0.48, \quad \mu(T)_{big} = \left|\sin\left(\frac{\pi}{2} - \frac{42}{50}\pi\right)\right| = 0.88$$

These membership values can be expressed as the following fuzzy sets:

μ (R) = {0.90/small, 0.43/medium}
μ (A) = {0.73/small, 0.68/medium}
μ (N) = {0.81/medium, 0.59/big}
μ (P) = {0.31/small, 0.95/medium}
μ (T) = {0.48/medium, 0.88/big}

There are $2^5 = 32$ combinations for the fuzzy sets. Excluding the invalid combinations, there are 16 rules fired for module size state *big* and 12 rules fired for module size state *medium*. By using the *max-min* compositional rule of inference operation, the membership value for the module size state (MSS) can be evaluated:

$$\mu(MSS)_{big} = \bigvee_{i=1}^{16} \left(\mu(R) \wedge \mu(A) \wedge \mu(N) \wedge \mu(P) \wedge \mu(T)\right) = 0.73$$

$$\mu(MSS)_{medium} = \bigvee_{j=1}^{12} \left(\mu(R) \wedge \mu(A) \wedge \mu(N) \wedge \mu(P) \wedge \mu(T)\right) = 0.48$$

Similarly, the module size state membership values can be expressed as the following fuzzy set:

μ(MSS) = {0.73/big, 0.48/medium}

The module size state is not a crisp value, but is in the form of a fuzzy set. A defuzzification method has to use to derive a crisp value from this fuzzy set. In this case, using the centre of gravity method [10], as shown in Fig. 3, a value of *33.25* is produced as follows:

$$MSS = \frac{\int_{10}^{35.45}\left[\mu(Y)_{medium} \times Y\right]dY + \int_{35.45}^{50}\left[\mu(Y)_{big} \times Y\right]dY}{\int_{10}^{35.45}\left[\mu(Y)_{medium}\right]dY + \int_{35.45}^{50}\left[\mu(Y)_{big}\right]dY} = 33.25$$

This value is a crisp value of the module size. Since the region of module size state fuzzy set ranges from 0 to 50, this value implies that the initial module size is slightly too high. Thus, the number of transistors within the module should be decreased. The module size adjustment process is based on the module size state to increase or decrease the module size. The fuzzy rules for the module size adjustment is given in the following:

rule 1: IF module size state is *small* THEN *increase transistors.*

rule 2: IF module size state is *medium* THEN *leave alone*.

rule 3: IF module size state is *big* THEN *decrease transistors.*

Since the *MSS = 33.25*, both rule 2 and rule 3 are fired. We have two module size adjustment fuzzy sets on the right side of Fig. 4(a) and Fig. 4(b), respectively. The union of these two fuzzy sets is illustrated in Fig. 4(c). Once again, the centre of gravity defuzzification technique is use to get a crisp value from the fuzzy set obtained after the union. The crisp value of the module size adjustment (MSA) fuzzy set is calculated as follows:

$$MSA = \frac{\int_{-20}^{-7.1}\left[\mu(Z)_{\text{decreasing } transistors} \times Z\right]dZ + \int_{-7.1}^{10}\left[\mu(Z)_{leaving\ alone} \times Z\right]dZ}{\int_{-20}^{-7.1}\left[\mu(Z)_{\text{decreasing } transistors}\right]dZ + \int_{-7.1}^{10}\left[\mu(Z)_{leaving\ alone}\right]dZ} = -0.047$$

This value means that the module size should be decreased *4.7*%; i.e., *5000 + 5000*$\times$(– 0.047) = *4765* transistors should be included in a module. As shown in Fig. 1, the inference process will be terminated until the module size variation rate converges to a predetermine value.

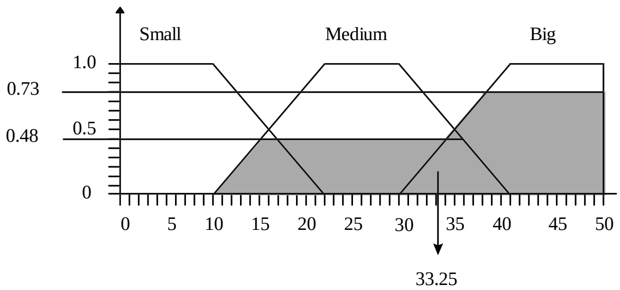
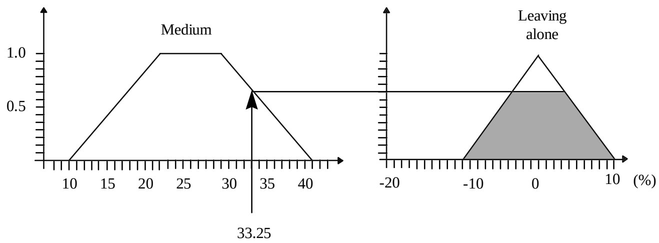
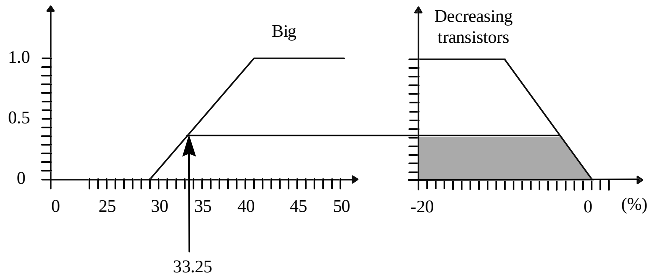


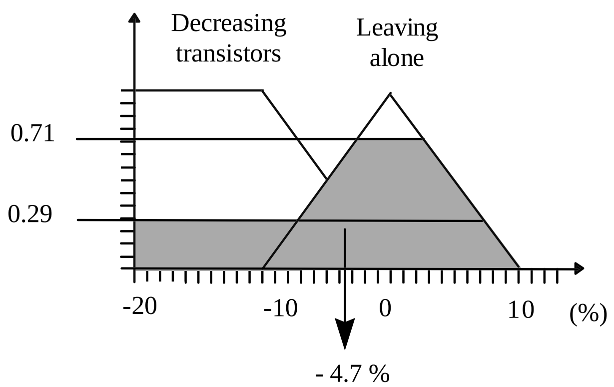
Fig. 3. Defuzzification using centre of gravity method.



(a). The output of module size adjustment fired by rule 2



(b). The output of module size adjustment fired by rule 3



(c). Defuzzification using the centre of gravity method

Fig. 4. Fuzzy inference process for module size adjustment.

4. CONCLUSION

Due to the imprecise measurement of IDDQ, statistics-based partitioning approaches, which use a fixed threshold as the module size decision base, are impractical. We have presented a fuzzy-based inference system to guide the module size decision for the partitioning of large CMOS circuits in BICT. We use five parameters, resolution, area overhead, noise immunity, performance, and testing time, as the function variables of the module size. These parameters are the input variables of our fuzzy system. The basic idea of our approach is based on the consideration that different design specifications result in different properties of chips. Our approach can provide wider aspects in the decision of the module size than existing approaches.

ACKNOWLEDGEMENT

This work was supported in part by the National Science Council of the Republic of China under Grant NSC84-2215-E-009-055.

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