

# Fuzzy-Based NC Application in Machine Tools with Efficient Analog CMOS Circuits

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## Abstract

For high speed applications, analog techniques are known to be faster than digital techniques with significantly less power consumption and silicon area requirements. This paper provides a CMOS realization of current-mode general-purpose fuzzy hardware and a design applied for superior motion control in NCs (numerical controls) used in machine tool industry. Nowadays, among other control systems, one of the major goals in machine tool systems is to integrate such systems which have the intelligence to determine optimal conditions for producing accurate and smooth workpiece. In this paper, an initial research, using the efficient analog CMOS circuitry, to optimize spindle motor speed in machine tools is described.

## 1. Introduction

In fuzzy systems there are three main steps: (1) fuzzification (membership function generation), (2) fuzzy inference, and (3) defuzzification. Excellent tutorial overviews on a utility of a fuzzy system and its application have been reported in many articles [1]-[4]. The number of practical applications of fuzzy controllers is currently growing at an accelerated rate, and fuzzy controllers are finding applications in many commercial consumer products.

Most fuzzy logic applications nowadays are still based on software controlled microprocessors. This results in relatively slow operation speed, not sufficient for real-time control problems.

A hardware implementation of a fuzzy logic controller using a PLD and a look-up table realized with a PROM was developed by Tan et al. [5]. PLDs such as PROMs, PLAs, PAL, or GAL offer an affordable technology, and they are relatively inexpensive devices. These devices can be programmed using a personal computer or a workstation. This PLD-based approach is simple yet has a relatively fast response time for

application that requires only a few inputs and A/D and D/A conversions for the system's analog signal processing. Thus, this technique using the PLD-based look-up table can also be a good candidate for NC applications.

Inherent imprecision of analog circuit, which has hindered their applications in other areas, is expected to be of little concern in fuzzy logic systems because such systems are inherently tolerant to imprecision as linguistic variables are used. Analog fuzzy chips also have an inherent compatibility with many sensors and transducers, such as a torque sensor, thermistor, and so forth.

For an NC application presented in this paper, a fuzzy logic controller with two analog inputs: (1) motor torque and (2) sound pressure level are to be sensed for the system in order to determine an optimal spindle motor speed. In machine tool industry, the machine operators have struggled determining optimal spindle motor speed, among other factors for optimal cutting conditions, to obtain required precision in their products. There has been no precise analytical solution to find optimal processing conditions in machine tools. Therefore, the operators have to be always careful and tense choosing cutting conditions. Otherwise, some workpiece could be out of tolerance and fail highly-demanded quality tests. In addition, if the spindle motor is not turning at proper speed, the motor as well as the tool which is attached to the spindle head would get unwanted load. This could cause serious breakdown to the motor and/or rapid tool wear. Hence, it is of interest to find optimal spindle speed so that the spindle motor and the attached tool can last longer, yielding better maintenance operation in terms of time and cost.

## 2. CMOS Model of a Fuzzy Logic Controller

The first stage of a fuzzy system is the fuzzifier block. A membership function of an analog consequent is

The approach taken in this design is not biased in the subthreshold region so that a significant driving capability is achieved. In the strong-inversion region, the MOS transistors have a power-law dependence on the gate bias voltages. The strong-inversion operation of MOS circuits provides the features of high current driving, large dynamic range, and high noise immunity. The circuit schematic of the proposed Gaussian-like membership function is shown in Fig. 1(a) and already described in details in [9]. Here the word, “Gaussian-like” is used because a shape of generated membership functions *resembles* a Gaussian function. However, note that the corners of those membership functions are rounded due to the nonlinearity of the CMOS transistors, and the shapes become parabolic if the transistors operate in the strong inversion, or exponential in case they operate in the weak inversion mode. The average of the two reference voltages determines the mean of a Gaussian-like curve, and the input voltage is applied to the gates of M1 and M4. For MOS transistors operating in the saturation region, the drain currents are approximated in a quadratic form and found in [7] and [9]. The output current  $I_{OUT}$  is then the sum of the two currents  $I_{D2}$  and  $I_{D4}$ , and it is derived by [7] and given as

The values of the control parameters  $\alpha_i$  and  $\beta_i$  specified in expression (2) are chosen to obtain a desired shape of Gaussian-like curves, as demonstrated in Fig. 1(b). If symmetrical curves are desired, the transistor sizes of the two differential pairs must be the same. The controllability of the shape of the output current can be achieved by varying the difference of the two reference voltages. As can be seen, the output current curve

sets  $I_{IN1}, I_{IN2}, \dots, I_{INn}$ . Therefore, the min circuit functions to detect the smallest current of a set of  $n$  given input currents, as described in [9] as

$$I_{MIN} = \min[I_{IN1}, I_{IN2}, \dots, I_{INn}] \quad (3)$$

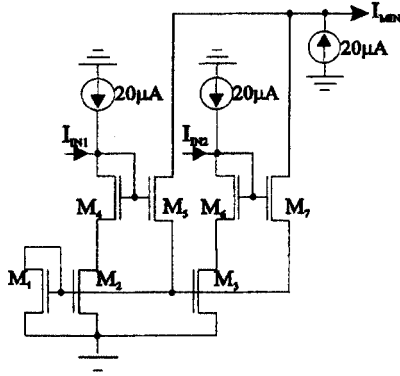


Fig. 2(a). Circuit schematic of the min operator[9]. All the transistors are of the same size.

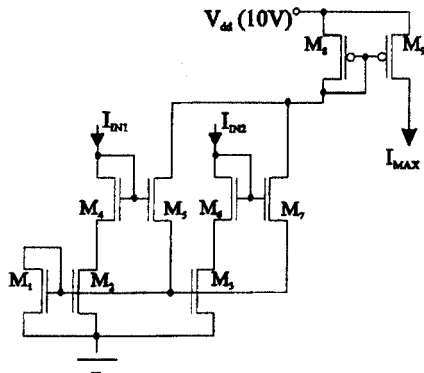


Fig. 2(b). Circuit schematic of the max operator[9]. All the transistors are of the same size.

While the max operator finds the union of two fuzzy sets  $I_{IN1}, I_{IN2}, \dots, I_{INn}$ , and the max circuit functions [9] such that

$$I_{MAX} = \max[I_{IN1}, I_{IN2}, \dots, I_{INn}] \quad (4)$$

The SPICE simulation of the min-max operators with two input currents is shown in Fig. 3.

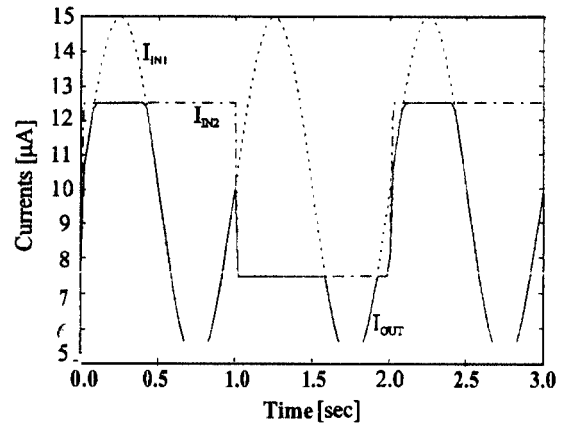


Fig. 3(a). Min circuit characteristics simulated with SPICE.

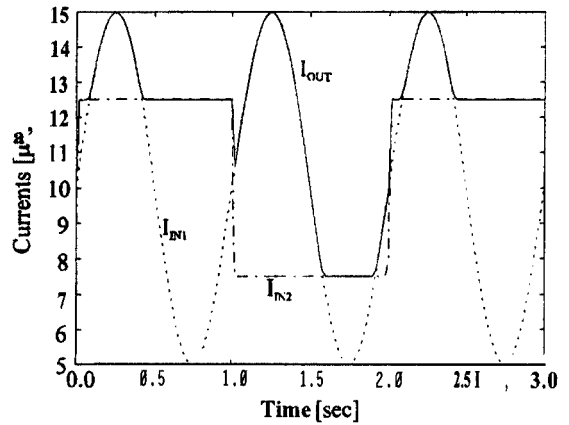


Fig. 3(b). Max circuit characteristics simulated with SPICE.

The last stage in a fuzzy logic controller is the defuzzifier. Its objective is to obtain a crisp deterministic value, on the universe of discourse, from a fuzzy value (membership function) by aggregating all individual conclusions from the previous stage, the fuzzy inference block. The centroid, or the center of gravity (C.G.), method is simple and the most popular defuzzification method. Its algorithm is typically given as

$$C.G. = \frac{\sum_{i=1}^n \mu(z)_i \cdot z_i}{\sum_{i=1}^n \mu(z)_i} \quad (5)$$

where  $n$  represents the number of fuzzy sets on the universe of discourse, and  $\mu(z)_i$  and  $z_i$  represent the membership function and the weighting value of the  $i$ -th fuzzy set, respectively. From a MOS analog circuit

point of view, division has always been a troublesome operation in terms of time and area. Many of the reported fuzzy controllers impose the condition that the denominator in expression (5) assumes the value 1 to avoid the division, or recur to the use of global normalization loops [4],[8],[9].

A defuzzifier circuit with a feedback loop [9] has a demerit on the operation speed due to the required convergence time. The proposed defuzzifier circuit, based on a current source normalization, overcomes this convergence time limitation by eliminating a feedback loop and reducing the number of transistors. Also, the accuracy is improved with a large open-loop gain, which then leads to a stable operation. The circuit is shown in Fig. 4. A similar approach with normalization and weighted sum [10] uses the  $n \times m$  fuzzy MIN variables as inputs to the defuzzifier block with  $n \times m$  fuzzy inputs to a fuzzy rule table. With the design [10], a MAX, i.e., OR-ing operation in a fuzzy rule evaluation is skipped. The circuit in Fig. 4 takes an advantage of Kirchhoff's current law for the signal summation and current mirrors for defuzzification weight multiplication in equation (5). The troublesome division problem is also avoided by making the denominator in expression (5) constant, and the output of the defuzzifier is thus quasi-normalized. As can be seen from Fig. 4, each max current obtained from the previous stage (max component of the min-max fuzzy inference block) is applied to the gate of the input  $n$ -channel MOS transistors (M1-M3), after converting each max current to its corresponding voltage (name them as  $V_{MAXi}$ ) using a linear Y-1 converter. When these transistors are operated under the saturation regime with a fixed source voltage, the drain current in each input transistor is directly proportional to the magnitude of the gate voltage or the  $V_{MAXi}$  voltage applied to the corresponding transistor. In other words, each drain current of the input transistors represents the corresponding max voltage. These drain currents are then multiplied with defuzzification weights  $z_i$  through  $p$ -channel current mirrors (M4-M9) and then aggregated to obtain the numerator part of expression (5). That is, the output current of the defuzzifier circuit after the weight multiplication and summation is expressed as

$$I_{OUT} = I_{D1}z_1 + I_{D2}z_2 + \dots + I_{Dn}z_n \quad (6)$$

which is equivalent to the following expression.

$$I_{NUM} = \sum_{i=1}^n I_{Di}z_i \quad (7)$$

Notice that the sum of the drain currents is equal to the current supplied by the current source, and this represents

the denominator part of expression (5) in its current form. That is,

$$I_{DEN} = \sum_{i=1}^n I_{Di} = I_{REF} \quad (8)$$

This condition is appropriate because each drain current of the input transistors is proportional to the corresponding gate voltage.

The circuit shown in Fig. 4 can be modified to multiply with negative weights using  $n$ -channel current mirrors. Therefore,  $p$ -channel current-mirrors are used to multiply with positive weights, which supply currents to the output node, and  $n$ -channel current-mirrors, on the other hand, are used to realize negative weights, which sink currents from the output node.

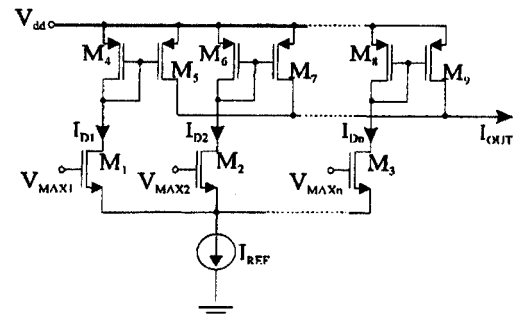


Fig. 4. Circuit schematic of the defuzzifier which avoids troublesome division process necessary in a conventional defuzzifier block.

### 3. Application for Fuzzy-Based NCs

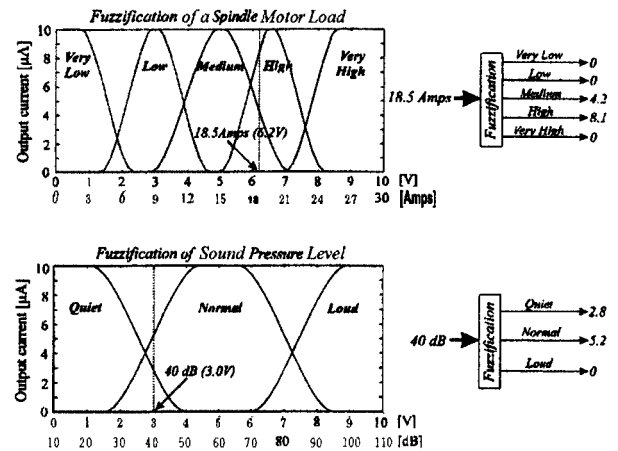
The proposed analog circuit has been simulated to see its functionality applied to a numerically controlled (NC) machine tools typically used in heavy industry. Machine tools are among the key issues of equipment in factory systems, and they require leading-edge technology in their controllers. For NC-based machine tools, an optimal spindle motor speed, among other factors, is difficult to estimate analytically to obtain an accurate and smooth cutting with milling and cutting tools. In fact, even though mathematical equations can be derived with conventional control techniques, the analytical results on the dynamic performance, the criteria for stability, and others may not be reliable because the mathematical model might not be exact. It is of interest to operate NC-based machine tools in real-time as cutting conditions change during its operation. A major goal in modern manufacturing systems is to integrate machine tools which have the intelligence to look after themselves and their peripheral devices and to determine optimal machining conditions [11].

The objective of this design here is to find an optimal spindle motor speed by sensing two inputs: (1) spindle motor torque and (2) cutting sound pressure level. The first input can be obtained by sensing a spindle motor current since the motor load is proportional to its current. The second input, sound pressure level, can be monitored by sampling the cutting sound with a small electric microphone. These two analog inputs are then described and categorized by linguistic variables as shown in Fig. 5. For the fuzzification process, the crisp inputs are first scaled and converted to voltages between 0 and 10V, then fuzzified within the scale of 0 to 10 $\mu$ A current output as seen from Fig. 5. Using this figure, the degree of association of each input fuzzy variable at any given crisp input can be found. For, example, a set of two crisp input readings, spindle motor current and sound pressure level, with values of 18.5A (6.2V) and 40dB (3.0V), respectively, gives the following set of input fuzzy variables for each input reading from Fig. 5. Usually, only one or two fuzzy input variables have a value different, from zero.

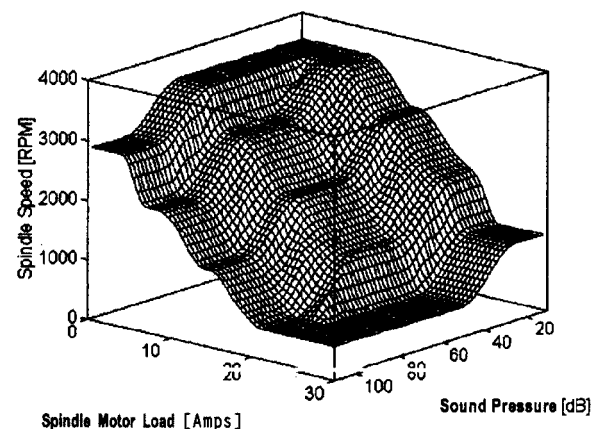
*Motor Current*  $\Rightarrow \{0.0\mu\text{A}, 0.0\mu\text{A}, 4.2\mu\text{A}, 8.1\mu\text{A}, 0.0\mu\text{A}\}$   
*Sound Pressure Level*  $\Rightarrow \{2.8\mu\text{A}, 5.2\mu\text{A}, 0.0\mu\text{A}\}$

This experience and knowledge is embedded in the linguistic-rule based description of the control strategy. The template-based approach is an approach partitioning the input and output space into a template to construct the rule-base representation in a grid of antecedents and consequences. This approach is used with proper knowledge-based rules, and then the min-max operation is performed for this fuzzy inference stage. Fig. 6 illustrates the simulated result of the control surface (input-output mapping characteristics) of this spindle motor speed controller with Gaussian-like input membership functions using the proposed circuit structures.

It is relatively easy to change the control surface of the fuzzy logic controller in accordance with the change of the system under control. If the center of the control surface needs to be pulled up, then the label (linguistic variable) of the consequent in the corresponding rule should be increased. It is apparent that the defuzzification weights in equation (5) also determines the control surface although this process is not illustrated in details. One method of finding these weights is to use fuzzy probabilities and an expert's experienced data. Of course, they can be adjusted by the concepts of learning, self-organizing, and adaptation by combining artificial neural networks. This fusion of a fuzzy logic controller and an artificial neural network is expected to improve system performance.



**Fig. 5.** Fuzzification process of spindle motor load and cutting sound pressure level. Five membership functions (linguistic labels) are used for fuzzification of spindle motor load, and three membership functions are used for the fuzzification of the sound pressure level.



**Fig. 6.** Output control surface of the spindle motor speed controller using Gaussian-like input membership functions.

In this particular design, only spindle motor torque and cutting sound pressure level are considered for the inputs to the controller. However, there exist other factors that contribute to machining conditions. Some of them are tool wear, workpiece material, workpiece size, and holding (chucking) pressure. It would be interesting to investigate further to determine optimal machining conditions including these factors as well. Another way to improve machining conditions might be to monitor cutting sound itself, and then a controller using artificial neural network that can recognize and identify cutting conditions [12] and corresponding optimal conditions as a feedback signal.

#### 4. Conclusions

A fuzzy logic controller applied for NCs in machine tools using an efficient analog CMOS architecture has been presented in this paper. In our previous studies [7][9], we were able to generate programmable membership functions for the fuzzification step and to give a very fast system performance with promising results. By utilizing the presented analog circuitry, a real-time computation of spindle motor control has been achieved, which will then give smoother workpiece surface conditions and more precise cutting conditions with machine tools. With optimized spindle motor speed using the fuzzy logic controller, the extra load to a spindle and a tool itself that is attached to the spindle head could be reduced significantly. This would yield a longer life in tool wear, which in turn, would benefit the machine users in terms of the tool cost and the tool maintenance time.

For the NC application presented in this paper, only spindle motor torque and sound pressure level are considered for the system inputs; however, other contributing factors should be included to form a more thorough system and to obtain a better performance.

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