Digitally Tuned Analog VLSI Controllers

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Abstract— **Digital controllers have historically enjoyed many advantages over those synthesized by analog electronics, but there are still some drawbacks to discrete-time implementations of controllers and signal processing algorithms: costly conversion of analog signals to digital and back, quantization errors, digital noise, time discretization, computation of signals by one CPU, and relatively large circuitry with limited processing speed. The key disadvantage of digitals systems is the signal latency due to A/D and D/A conversion time and relatively slow signal processing. The key disadvantages of analog signal processing are: limited accuracy due to limited tolerances of transistors and limited flexibility for adaptation. When digitally tuned analog controllers are used, then both disadvantages can be eliminated. Limited tolerances of circuit elements can be also compensated by digital tuning. Furthermore, this approach gives the possibility to reconfigure the system. Digitally controlled analog circuits have the following advantages: lower cost, high speed and small signal latency, parallel processing, direct implementation of continuous time designs, and smaller system noise important for a precision control.**

I. INTRODUCTION

During the past three decades, digital systems have gained a dominant role in industrial control systems [1][2][3]. Their main advantages are high accuracy, repeatability, and portability. Properties of these controllers can be easily adjusted by storing different information in computer memories. The majority of industrial plant dynamics are slow enough so that digital processors have enough time to handle the process. In cases when faster responses are required dedicated signal processors are used. Key elements of all digital systems are analog-to-digital and digital-to-analog converters.

Digital systems have several drawbacks:

(1) There is signal quantization in both time and magnitude. To lower these effects, higher sampling frequencies and higher conversion resolutions must be used, which together lead to significant cost increase.

(2) In most cases, controller computations are done in a serial sequence by one central processing unit.

(3) Our surrounding world has an analog nature and therefore inherited part of digital control systems are costly A/D and D/A converters. Consequently, digital control systems require relatively large and complex signal conversion circuits.

(4) Signal conversions introduce latencies that must be compensated in control system design.

The block diagram of a typical high-performance digital control circuit is shown in Fig. 1.

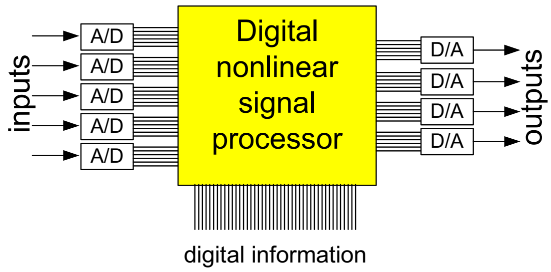


Fig. 1. Block diagram of a digital control circuit

All digital signal processing systems must transform analog input and output signals. In contrast to digital control electronics, the analog IC solution has the potential to bypass many problems. Potential advantages of analog IC electronics for nonlinear system include:

1 Lower cost, energy consumption and package size
2 Inherently high speed
3 Parallel processing
4 Direct implementation of continuous time designs

Analog systems are much simpler (see Fig. 2) and faster [4][5][6][7][8] but they have two major drawbacks:

(1) Their accuracies are restricted due to limited tolerances of circuit elements.

(2) They have limited flexibility for changing controller parameters. In most cases, even minor tuning requires changing values of multiple circuit elements.

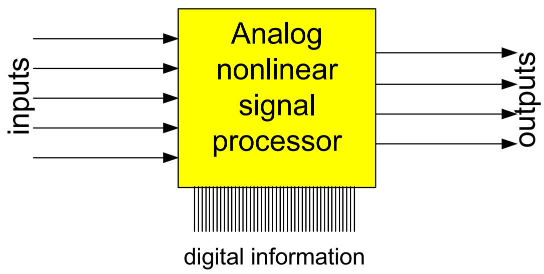


Fig. 2. Block diagram of a digitally controlled analog control circuit.

One may notice that any dynamic nonlinear system can be described by the set of nonlinear state equations (1).

$$\begin{aligned} \dot{y}_1 &= f_1(x_1, \ldots, x_n, y_1, \ldots, y_n) \\ \dot{y}_2 &= f_2(x_1, \ldots, x_n, y_1, \ldots, y_n) \\ &\vdots \\ \dot{y}_n &= f_n(x_1, \ldots, x_n, y_1, \ldots, y_n) \end{aligned} \tag{1}$$

Such systems can be implemented as a composition of analog integrators and nonlinear terms as shown in Fig. 3.

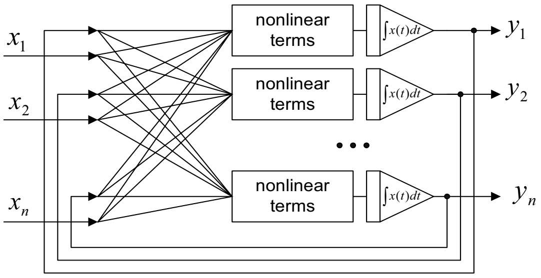


Fig. 3. Dynamic nonlinear system described by (1) implemented with a set of integrators and nonlinear terms.

Implementations of analog integrators on silicon chips are relatively simple, requiring only a capacitance and operational or transconductance amplifier. In the case of linear systems, the circuit can be simplified as shown in Fig 4.

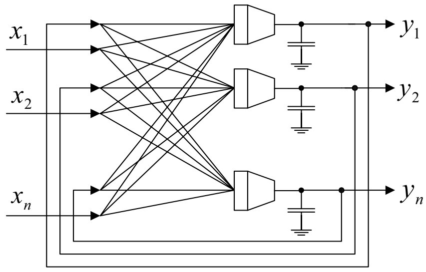


Fig. 4. Dynamic linear system with capacitors and multi-input transconductance amplifiers having digitally controlled gains.

A multi-input transconductance amplifer implementation is shown in Fig. 5. Bias currents I_A and I_B can be digitally adjusted to modify the gains g_{MA} and g_{MB}, respectively. Shown in Fig. 6 is a linear filter example.

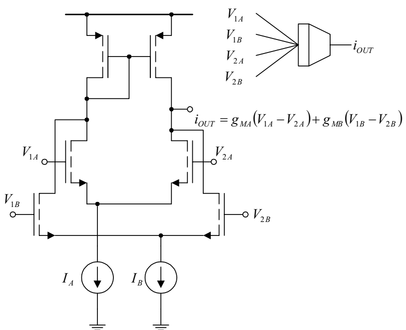
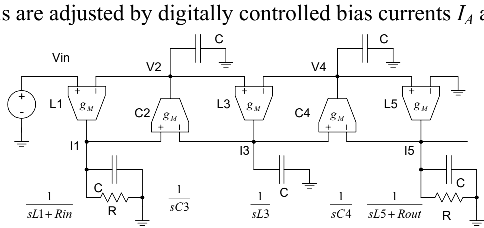


Fig. 5. Transconductance amplifier with a multiple inputs. Gains are adjusted by digitally controlled bias currents I_A and I_B



Fig, 6. Fifth order low-pass Chebyshev filter using ladder prototype.

Characteristics of transconductance amplifiers can be digitally adjusted to obtain proper characteristics as shown in Fig. 7.

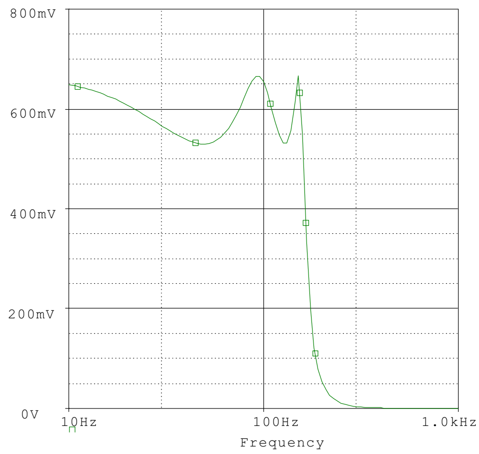


Fig. 7. Frequency response for the filter of Fig. 6.

Low noise transconductance active filters can be used to improve signal to noise ratio. These types of filters do not produce the digital noise that is an inherent property of switched capacitor and switched current filters. They can also operate over a much broader frequency range, and their characteristics can be digitally controlled. An example is shown in Fig. 8

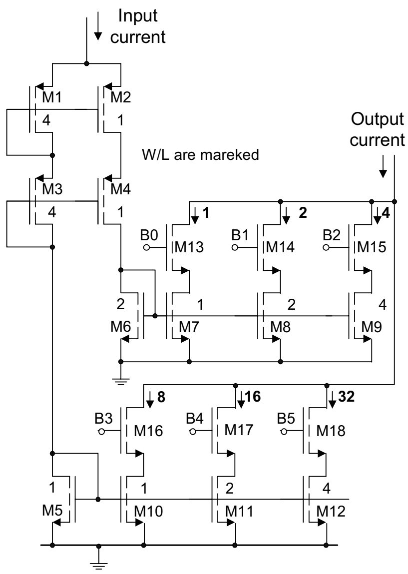


Fig. 8. Circuit with a digitally programmable current gain having 6 bit range. A similar circuitry can be used to program gains of transconductance amplifiers. The chip space use is very effective since the maximum ratio in the transistor size is only four. With traditional approach these ratios could be as large as 64.

It is more difficult to implement nonlinear terms with multiple inputs. These nonlinear blocks can be implemented as universal elements using neural networks [9][10][11] or fuzzy systems [12][13]. In both cases nonlinear terms can be digitally controlled. In the case of neural networks it requires digitally controlled weights, while in the fuzzy systems parameters of fuzzifiers and defuzzifiers and be digitally adjusted.

The digitally controlled analog system shown in Fig. 2 has very fast processing time, limited only by signal propagation through VLSI circuitry. There is no need for A/D and D/A converters, and all signal processing is done in analog circuitry. At the same time the system architecture is controlled digitally. These digital inputs have to adjust system parameters and very slow digital processing is required. At the same time limited tolerances of circuit transistors can be also compensated by externally stored digital information. The digitally adjusted analog controller concept presented in the Fig. 2 eliminates two major drawbacks of purely analog controllers: limited accuracy and limited flexibility. At the same time the processing speed can be increased and control circuit complexity reduced.

Development of digitally controlled nonlinear analog circuitry is the major challenge. There are three possible approaches: fuzzy systems, neural networks, and application specific design of nonlinear circuits.

II. FUZZY BASED SYSTEMS

The block diagram of a typical fuzzy system is shown in Fig. 9.

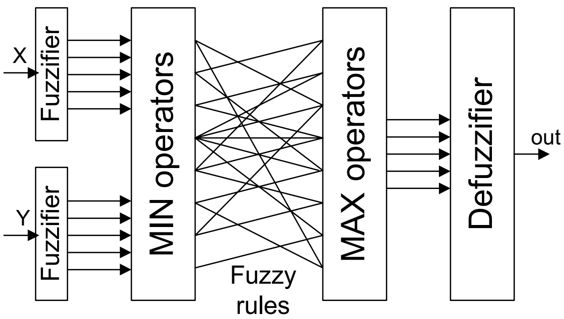


Fig. 9. Block diagram of a fuzzy system

At the left side of the diagram, analog inputs are converted into sets of fuzzy variables (fuzzifier). For each analog input, several fuzzy variables typically are generated. Each fuzzy variable has an analog value between zero and one. In the center of the diagram, a fuzzy logic is applied to the input fuzzy variables and a resulting set of output variables is generated. The rightmost block of the diagram represents *defuzzification*, where one or more output analog variables are generated from a set of output fuzzy variables.

The purpose of fuzzification is to convert an analog variable input into a set of fuzzy variables. For higher accuracy, more fuzzy variables are chosen. For proper design of the fuzzification stage, certain practical rules should be used:

- Each point of the input analog variable should belong to at least one and no more than two membership functions.
- For overlapping functions, the sum of two membership functions must not be larger than one. This also means that overlaps must not cross the points of maximum values (ones).
- For higher accuracy, more membership functions should be used. However, very dense functions can lead to frequent controller action (also known as "hunting") and sometimes to system instability.

Implementations of fuzzifiers in VLSI circuits are not difficult [13]. For example the circuit of Fig. 10, with one current source and 10 transistors, is capable of producing the six membership functions shown in Fig. 11. These membership functions may have different shapes such as step (I1, I6), trapezoidal (I3, I5), triangular (I4), or Gaussian (I2).

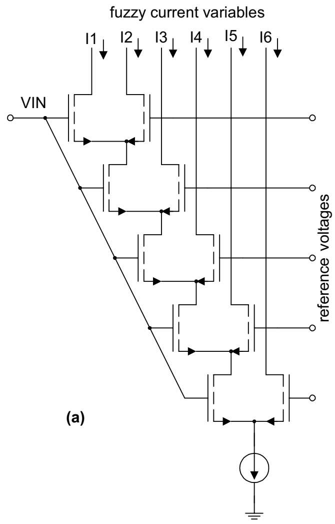


Fig. 10. Circuit diagram of a fuzzifier.

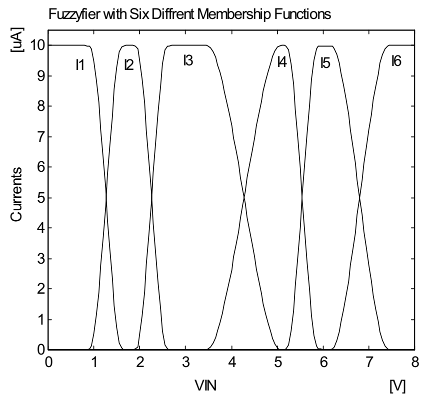


Fig. 11. Membership functions produced by fuzzifier circuit in Fig. 10.

In voltage mode operation, analog circuit implementations of MAX and MIN operators are very simple. In the case of the current mode operation, as in the case of the fuzzifier circuit of Fig. 10, the circuit is slightly more complex (see Fig. 12). By changing signal polarity the MAX circuit can be converted to a MIN circuit and vice versa.

The most difficult block to implement in analog circuit hardware is the defuzzifier. It usually requires signal division, which leads to very complicated design. When a simplified singleton type of defuzzifier is used, the defuzzifier can be built using feedback [Ota, 1996], or it can use a normalization circuit and weighted summing [Takagi, 89][Rodriguez, 95]. The feedback approach has limited accuracy. To improve accuracy, large open-loop gain is required, which can lead to a stability problem. It is much easier to implement the Takagi-Sugeno defuzzifier.

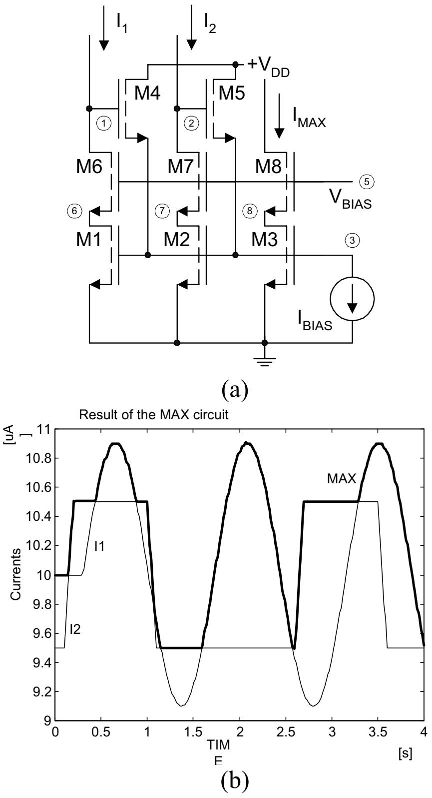


Fig. 12. Current mode MAX circuit for fuzzy systems (a) circuit diagram, (b) obtained result.

If the sum of fuzzy signals coming out of the fuzzy rule is kept constant, then signals are normalized and simple weight summing circuit works as the singleton defuzzifier (Fig. 13). Such fuzzy system has flexibility for digital control of its parameters.

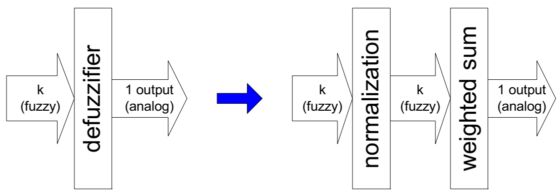


Fig. 13. Takagi-Sugeno type defuzzifier

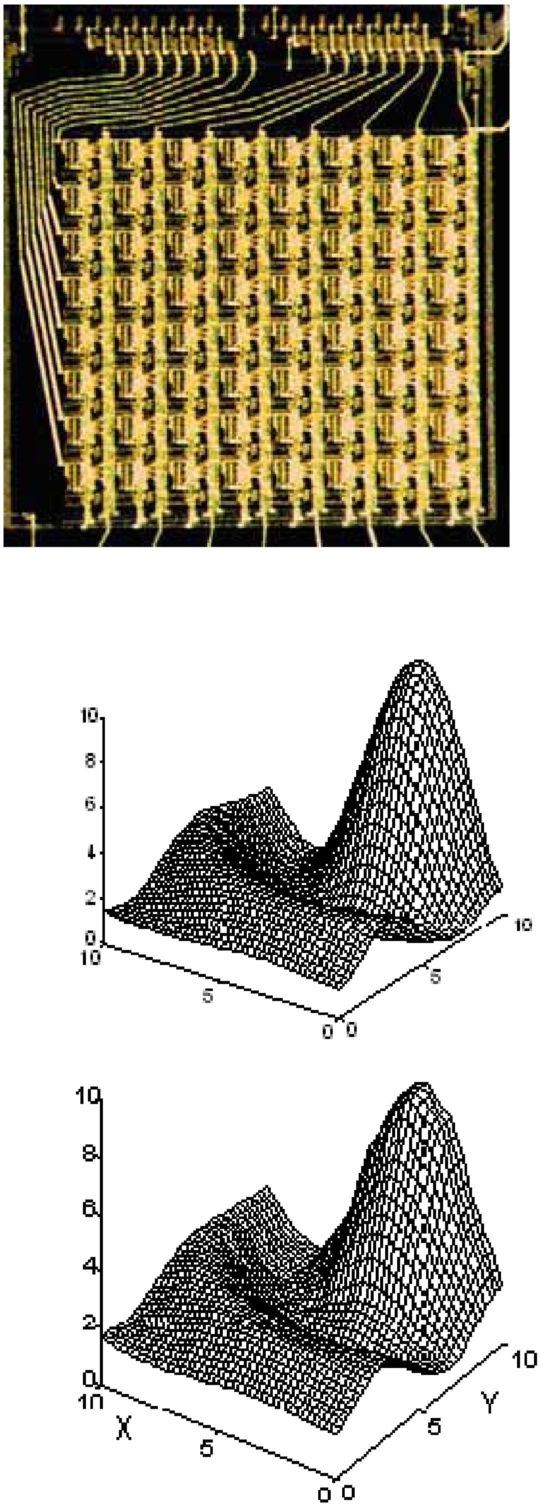
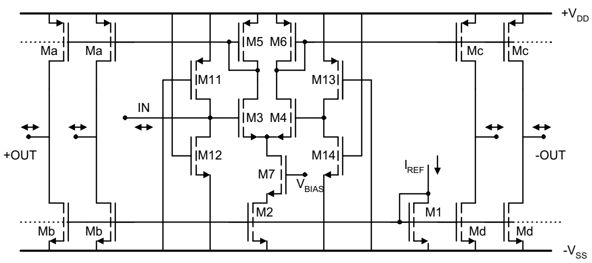


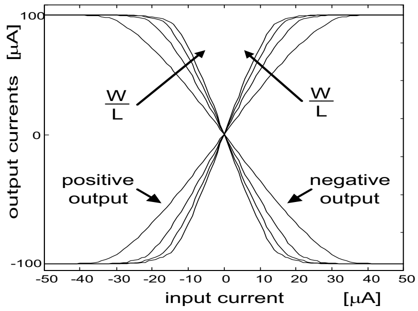
Fig. 14. VLSI implementation of two-dimensional control surface using fuzzy systems (a) microphotograph of fuzzy chip (b) Required control surface and (c) measured control surface.

III. NEURAL NETWORK SYSTEMS

Implementations of neurons in VLSI chips are relatively simple. Note, that every differential pair generates a sigmoidal type nonlinear function that is suitable for neural processing. It is much more difficult however to implement weights. In other words weight circuits are usually much more complicated than the neuron circuit itself [14]. When a digital adjustment is required for each weight, circuits similar to that shown in Fig. 15 can be used. When fixed values of weights can be used, then the circuit can be significantly simplified. Each weight can be set by proper W/L ratios of output transistors as shown in Fig. 15b. By taking signals from different outputs of the differential pairs, both positive and negative weights can be implemented.



(a)



(b)

Fig. 15 Neuron circuit with weights determined by W/L ratios of output transistors.

IV. COMPARISON OF FUZZY AND NEURAL CIRCUITS

Digital adjustment of analog controllers has been introduced above, and both fuzzy and neural network implementations of nonlinear functions discussed. In hardware, fuzzy systems dominate current trends in both microprocessor applications [13] and in custom designed VLSI chips [14]. Control surfaces obtained from certain implementations of fuzzy controllers are rough, which can cause poor control. On the other hand, neural networks usually require a computation of sigmoidal activation functions (e.g. tangent hyperbolic), which are often too complex for simple microprocessors. When the tangent hyperbolic function is replaced by the Elliott function

$$
\begin{aligned}
f(net) &= \tanh(net) \\
&= \frac{2}{1-\exp\left(-2net\right)} - 1 \\
&\approx \frac{net}{1+|net|}
\end{aligned}
\qquad (2)
$$

then the computations are relatively simple and the results are almost as good as in the case of a sigmoidal function [12]. With this approach, neural network implementations resulted with shorter code, faster operation, and much more accurate results. Fig. 16 shows the comparison of several controllers for the same desired control surface implemented in the popular HC11 microcontroller, using various fuzzy and neural network architectures. Table 1 shows the comparison of errors, processing times and lengths of code.

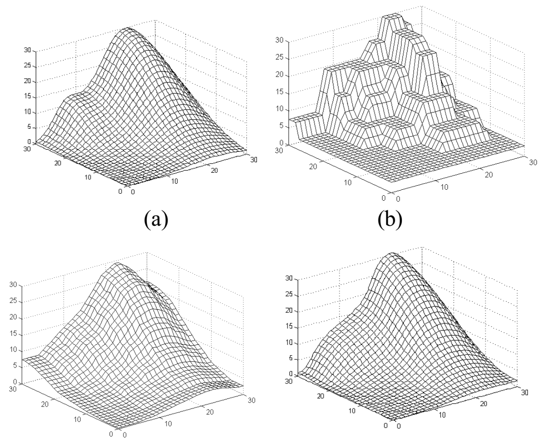


Fig. 16. Control surfaces for various controllers. (a). Required control surface, (b) Fuzzy Mamdani type with trapezoidal membership functions, (c) Fuzzy Tagagi-Sugeno type with triangular membership functions, (d) neural controller with six neurons in 2-1-1-1-1-1-1 architecture.

V. APPLICATION SPECIFIC DESIGN OF NONLINEAR CIRCUITSMP

In many cases very specific nonlinear functions have to be implemented and for that purpose often fuzzy and neural technology may be deemed too complex for practical applications. For that purpose a specific VLSI circuits can be developed to implement the desired nonlinear function. For example Fig. 17 shows the circuit diagram which implements a cosine function.

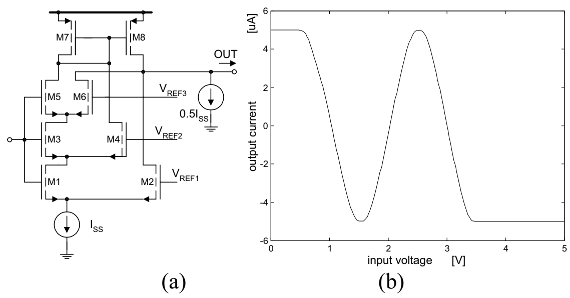


Fig. 17. Implementation of cosine nonlinear function (a) circuit diagram, (b) obtained result

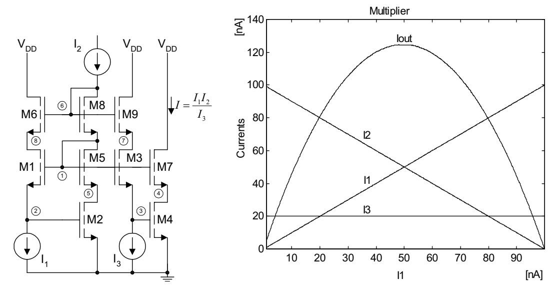


Fig.. 18. VLSI implementation of signal divider (a) circuit diagram, (b) and (c) obtained result

Fig. 18 shows a signal divider as another example of nonlinear analog signal processing. Many circuits are possible for creating various nonlinear function using nonlinear characteristics of semiconductor devices. All theses circuits are relatively simple and fast. Their main disadvantage is that obtained functions are not accurate, and may strongly depend on element tolerances. However in many control applications this is not the serious issue since nonlinear functions are often used to "linearize" systems so robust linear control methods can be applied. To be effective this linearization need not to be perfect as long major nonlinearities are eliminated.

VI. CONCLUSION

In this paper, the authors propose a new class of control system electronics: digitally tuned analog VLSI controllers. Such controllers possess the signal processing advantages of analog VLSI circuits (lower cost, low energy consumption, small package size, inherently high speed, natural parallelism), while also eliminating the two chief drawbacks (inaccuracy and poor flexibility). Digitally tuned analog VLSI controllers are an enabling technology for advanced nonlinear control of plants having fast dynamics. A key element of the digitally tuned analog VLSI controller is the nonlinear weighting function - in this work, implementations using either fuzzy system or neural processing are considered.

Fuzzy controllers do have several advantages such as simple rule based design, but they usually produce relatively raw control surfaces, which are not acceptable for precision control [7]. These fuzzy control surfaces also exhibit larger errors. With the neural network approach, errors are smaller and the resulting control surfaces are very smooth.

The main disadvantage of neural systems is that their design process is much more complicated. Design problems are related not only to the selection of a proper architecture, but also finding optimum values of weights to fulfill expected circuit requirements.

With digitally tuned neural networks weights are quantized and this limits accuracy of such networks. A significant drawback of fuzzy system is fact that the number of inputs there are significantly limited (in most cases fuzzy system may not have more than 3 inputs. This limitation is much les severe when neural system is used.

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