Fuzzy Controllers CMOS Implementation

V. VARSHAVSKY [1], V. MARAKHOVSKY[2], I. LEVIN[3], N. KRAVCHENKO[4]
[1] Advanced Logic Projects Inc., JAPAN,
[2] The University of Aizu, JAPAN
[3,4] Bar Ilan University, ISRAEL

Abstract: - The subject of the study is hardware design of fuzzy controllers as CMOS analog devices on the base of controller descriptions in the view of multi-valued logical functions. A functional completeness of summing amplifier with saturation in an arbitrary-valued logic is proven that gives a theoretical background for analog implementation of fuzzy devices. Compared with the traditional approach based on explicit fuzzification, fuzzy inference, and defuzzification procedures analog fuzzy implementation has the advantages of higher speed, lower power consumption, smaller die area and more. The paper illustrates a design example for real industrial fuzzy controller and provides SPICE simulation results of its functioning.

Key-Words: - Fuzzy Logic, Fuzzy Controller, Multi-Valued Logic Functions, Functional Completeness, Summing Amplifier with Saturation.

1 Introduction

Wide spread of the fuzzy control and high effectiveness of its applications in a grate extend is determined by formalization opportunities of designer “fuzzy” (flexible”) representations about necessary behavior of a controller. These representations usually are formulated in the view of logical (fuzzy) rules under linguistic variables of a type “If A then B”. The linguistic variables themselves are quality characteristics of input signals of types “warm”, “cool”, “high”, “low”, “fast”, “slow” and so on.

As a rule, or at least in a grate part of applications, a fuzzy controller is a transformer of input analog signals into an analog output signal.

A linguistic variable is a “subjective” characteristic of an input analog variable and the input variable transformation is given by membership functions determining for each value of the input variable the set of weighted values corresponding linguistic variables. This procedure is called a fuzzification and it contains as its composite part the analog-digital transformation.

A set of combinations of weighted linguistic variables corresponds to each value combination of input analog variables. On the base of a fuzzy rules system and of fuzzy inference rules it is possible to receive the set of weighted values of the output linguistic variable. Using these values, membership functions of the output variable, and one of the several known methods of defuzzification it is possible to form the value of the analog output variable. The defuzzification procedure also includes digital-analog transformation.

At present the most wide-spread way of fuzzy logic control implementation is using the programmable fuzzy controllers, which are available on the market together with the means of computer aided programming. However, in spite of the implementation evidence and fuzzy controllers’ accessibility this approach to implementation possesses some disadvantages, e.g. such as high cost and low throughput (that is especially important when fuzzy control in the control contour is used) etc.

In this work we are going to show that for a sufficient wide set of problems a fuzzy controller can be implemented as a rather simple CMOS device that is used as embedded system or IP core. That is the basic idea of our suggestion?

A fuzzy controller is a deterministic device, for which one and only one value of the output analog variable corresponds to each value combination of the input analog variables. It means that the fuzzy controller should realize an analog function $Y = f(x_1, x_2, ..., x_n)$ [1].

There are two important questions:

1. How to transit from standard specification of a fuzzy logic function to the specification of corresponding analog function?
2. How to transit from an analog function specification and/or from standard specification of a fuzzy logic function to corresponding CMOS implementation?

First of all, let us address to membership functions. In most cases [1 – 3], membership functions have a triangle or trapeze view (see fig.1).

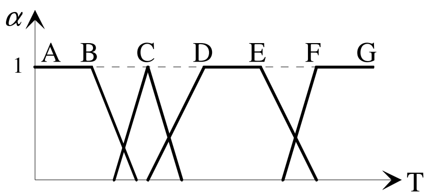

Figure 1. Types of membership functions.

In fig.1 linguistic points A and B are "cold", C – "fresh", D and E – "worm", F and G – "hot". These points determine the connection of the linguistic variables with values of the analog variable T (in our case T is temperature). Relatively these points and similar points for other input variables we can compose a table of fuzzy rules connecting value combinations of input linguistic variables with values of the output linguistic variable.

On the base of membership functions we can put into accordance to the input and output linguistic variables a set of integer numbers splitting by appropriate way all diapason of changing of corresponding analog variables. Then the table of fuzzy rules will to determine by obvious way the function of multi-valued logic, values of which define the digit representation of the output linguistic variable on chosen value combinations of multi-valued input variables.

In [4 – 6] we have shown that the analog threshold function having the fallowing view

$$y(X) = \begin{cases} +k & \text{if } \sum_{j=1}^{n} \omega_j \cdot x_j \le -k \\ -\sum_{j=1}^{n} \omega_j \cdot x_j & \text{if } k > \sum_{j=1}^{n} \omega_j \cdot x_j > -k \\ -k & \text{if } \sum_{j=1}^{n} \omega_j \cdot x_j \ge +k \end{cases} \quad (1)$$

conforms together with constants a functionally complete system in the (2*k*+1)-valued logic. This function can be implemented on the base of summing amplifier with saturation [5].

2 Summing Amplifier as a Multi-Valued Logical Element

Summing amplifier's behavior, accurate to the members of the infinitesimal order that is determined by the amplifier's gain factor in disconnected condition (fig.2), is described as follows:

$$V_{out} = \begin{cases} V_{dd} & \text{if } \sum_{j=1}^{n} \frac{R_0}{R_j}(V_j - \frac{V_{dd}}{2}) \le -\frac{V_{dd}}{2} \\ \frac{V_{dd}}{2} - \sum_{j=1}^{n} \frac{R_0}{R_j}(V_j - \frac{V_{dd}}{2}) & \text{in other cases} \\ 0 & \text{if } \frac{V_{dd}}{2} \le \sum_{j=1}^{n} \frac{R_0}{R_j}(V_j - \frac{V_{dd}}{2}) \end{cases} \quad (2)$$

where V_{dd} – the supply voltage, V_j – the voltage on j[th] input, R_j – the resistance of j[th] input, R_0 – the feedback resistance, and $V_{dd}/2$ – the midpoint of the supply voltage.

Dependence of V_{out} on $\sum_{j=1}^{n} \frac{R_0}{R_j} \cdot (V_j - \frac{V_{dd}}{2})$ is shown in fig.3,a.

Let us split the source voltage V_{dd} on $m = 2k+1$ voltage levels. Then replacing the input voltages V_j by m-valued logical variables

[1] We shall notice that in suppressing majority of publications on fuzzy controllers this function is given as a response surface and practically without exception this surface has a piece-linear view.

$x_j = \frac{2 \cdot V_j - V_{dd}}{V_{dd}} \cdot k$ and the output voltage V_{out} by m-valued variable y and designating $R_0 / R_j = \omega_j$ the system (2) can be represented as (1). Graphical view of (1) is shown in fig.3,b.

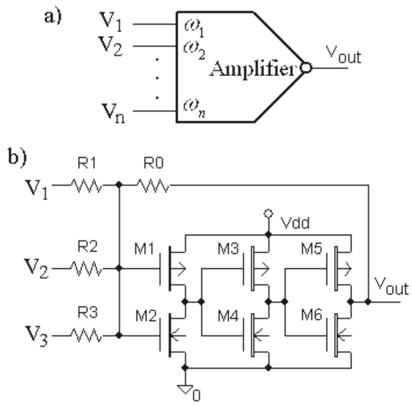

Figure 2. Summing amplifier: general structure (a); CMOS implementation using symmetrical invertors (b).

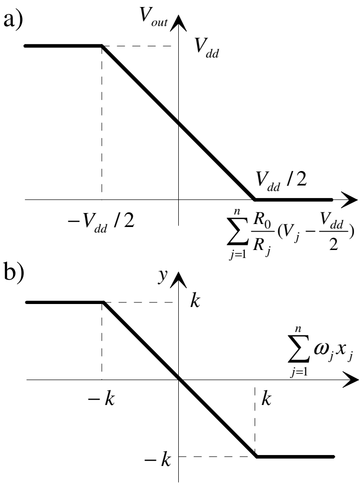

Figure 3. Summing amplifier's behavior: within voltage coordinates (a); within multi-valued variables coordinates (b).

Later on, we will call the functional element, whose behavior is determined by the system (1), a multi-valued threshold element. In the simplest case when $\omega_j = 1,\ j = 1,2,3$, we will call it the majority element and designate as $maj(x_1, x_2, x_3)$.

The basic operation (or set of basic operations) is called functionally completed in arbitrary-valued logic, if any function of this logic can be represented as superposition of basic operations.

There are some known functionally completed sets of functions. It is clear, that for proving functional completeness of some new function it is sufficient to show that the functions of the known functionally completed set can be represented as superposition of the considered function. One of functionally completed functions in m-valued logic is the Webb's function [7]:

$$w(x, y) = [\max(x, y) + 1]_{\mathrm{mod}\, m}. \qquad (3)$$

Therefore, for proving functional completeness of threshold operation in multi-valued logic it is sufficient to show how the Webb's function can be represented through this operation.

First, let us represent the function $\max(x_1, x_2)$ by threshold functions. To do this let us consider the function $f_a(x)$ diagram, such as

$$f_a(x) = \max(x, a) = \begin{cases} a & \text{if} \quad a \ge x \\ x & \text{if} \quad x > a \end{cases}. \qquad (4)$$

This function diagram is shown in fig.4,a.

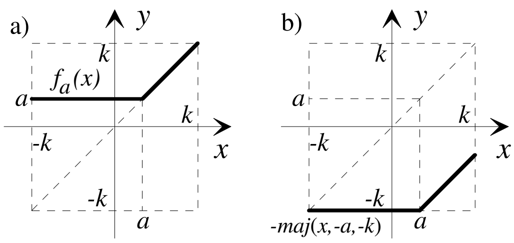

Figure 4. Diagrams of $f_a(x)$ (a) and $-maj(x,-a,-k)$ (b) functions.

The $-maj(x,-a,-k)$ function diagram is shown in fig.4,b. Actually, as far as $x < a$ $x - a - k < -k$ and $-maj(x,-a,-k) = -k$. Note that for all x values,

$$f_a(x) - maj(x,-a,-k) = a - k$$

as it follows from fig.4, hence

$$f_a(x) = -maj[maj(x,-a,-k), a, -k]. \qquad (5)$$

Taking into consideration that $-maj(a,b,c) = maj(-a,-b,-c)$, it follows from (5) that

$$\max(x_1, x_2) = maj(maj(-x_1, x_2, k), -x_2, k). \qquad (6)$$

Now let us consider the function $(x+1)_{\mathrm{mod}\,m}$ representation by threshold functions. To make it clear let us turn to the sequence of pictures fig.5.

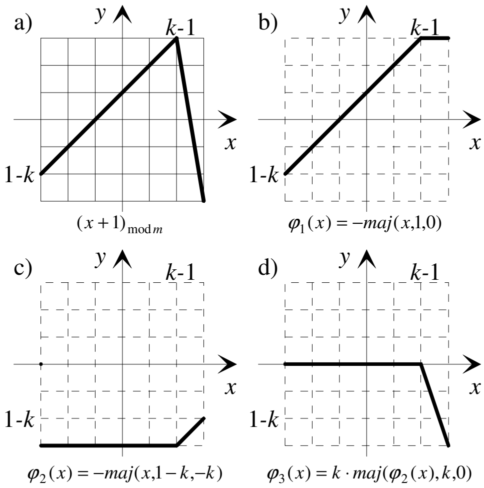

Figure 5. Implementation of $(x+1)_{\mathrm{mod}\,m}$ function.

From fig.5 it is easy to see that

$$(x+1)_{\mathrm{mod}\,m} = \varphi_1(x) + 2\varphi_3(x)$$

and obviously, this function can be implemented on threshold elements too. Hence, the functional completeness of the summing amplifier in arbitrary-valued logic is shown.

It is naturally that the proof procedure of functional completeness does not give information about methods of effective synthesis. The methods of synthesizing circuits in the proposed base are to be developed in future. However, as it will be shown below, for a number of real circuits the proposed base allows designing simple and efficient circuits.

3 Fuzzy Devices as Multi-Valued and Analog Circuits

Conventional implementation of fuzzy devices usually has the structure shown in fig.6. Analog variables $X = \{x_1, x_2, ..., x_n\}$ go the fuzzy device input. Fuzzifier converts a set of analog variables x_j into that of weighted linguistic (digital) variables $A = \{a_1, a_2, ..., a_n\}$.

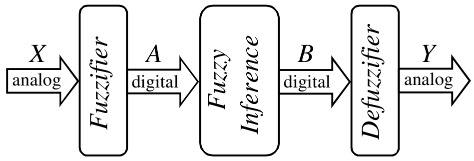

Figure 6. Fuzzy device structure.

Fuzzy Inference block based on the fuzzy rules generates a set of weighted linguistic variables values $B = \{b_1, b_2, ..., b_k\}$.

Defuzzifier converts a set of weighted linguistic (digital) variables $B = \{b_1, b_2, ..., b_k\}$ into a set of output analog variables $Y = \{y_1, y_2, ..., y_k\}$.

As a rule, fuzzifier and defuzzifier are implemented as AD and DA (analog-digital and digital-analog) converters, i.e. by hardware implementation. Fuzzy inference is usually implemented as microprocessor software.

On the other hand, there is the set of output analog variables, which values unambiguously corresponds to each set of input analog variable values; hence a fuzzy device could be specified as a functional analog of signal converter

$$Y(X) = \{y_1(X), y_2(X), ..., y_k(X)\}$$

and its output Y determines a system of n-dimensional surfaces. In cases of sufficient simple membership functions (in known publications such functions are in majority), for fuzzy controller implementations as analog devices it is sufficient to provide a piecewise-linear connection between a couples of points calculated as adjacent values of a multi-valued logic function.

Let $m = 2k+1$ linguistic variable a_j values correspond to analog variable x_j. Then basing on fuzzy rules system, we can specify a system of m-valued logic functions, as follows:

$$B(a_1, a_2, ... a_n) = \{b_1(A), b_2(A), ..., b_k(A)\}. \quad (7)$$

Note that most publications describing fuzzy controllers contain the tables, specifying fuzzy controllers' behavior as (7).

Let us consider an example. This example is taken from [9]: *"Design of a Rule-Based Fuzzy Controller for the Pitch Axis of an Unmanned Research Vehicle"*.

The fuzzy control rules for the considered device depend on the error value $e = ref - output$ and changing of error $ce = \frac{old\,e - new\,e}{sampling\ period}$. Fuzzifier brings seven levels for each of input linguistic variables (NB – negative big; NM – negative middle; NS – negative small; ZO – zero; PS – positive small; PM – positive middle; PB – positive big). The output has the same seven gradations. The corresponding 49 fuzzy rules are represented in Table 1.

Table of Fuzzy Rules. **Table 1**

		e						
		NB	NM	NS	ZO	PS	PM	PB
ce	NB	ZO	PS	PM	PB	PB	PB	PB
	NM	NS	ZO	PS	PM	PB	PB	PB
	NS	NM	NS	ZO	PS	PM	PB	PB
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NB	NB	NM	NS	ZO	PS	PM
	PM	NB	NB	NB	NM	NS	ZO	PS
	PB	NB	NB	NB	NB	NM	NS	ZO

Let us split evenly the source voltage (e.g. 3.5V) onto seven logical levels corresponding to linguistic levels. Then table 2 will represent table 1 as the function of seven-valued logic.

The Seven-Valued Function. **Table 2**

		e						
		-3	-2	-1	0	1	2	3
ce	-3	0	1	2	3	3	3	3
	-2	-1	0	1	2	3	3	3
	-1	-2	-1	0	1	2	3	3
	0	-3	-2	-1	0	1	2	3
	1	-3	-3	-2	-1	0	1	2
	2	-3	-3	-3	-2	-1	0	1
	3	-3	-3	-3	-3	-2	-1	0

It is seen from table 2 that the function is symmetric with respect to "North-West – South-East" diagonal and depends on $e - ce$. This kind of dependence is shown in fig.7.

It apparently follows from comparison of fig.3 and fig.7 that in order to reproduce the function specified by table 2 it is sufficient to have one two-input summing amplifier and one inverter.

Note that inversion of logic variables lying within $-k \div +k$ interval is the operation of diametric negation $\overline{x} = -x$; the operation $\overline{V_{out}} = V_{dd} - V_{in}$ corresponds to it in the space of summing amplifiers' output voltages. Thus CMOS circuit containing 12 transistors and 5 resistors, which implements our function, is shown in fig.8.

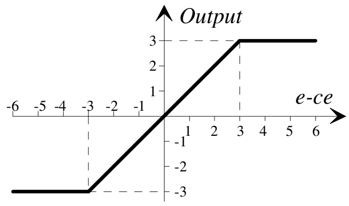

Figure 7. Graphical representation of the function specified by table 2.

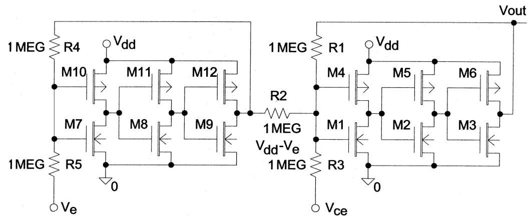

Figure 8. CMOS implementation of the fuzzy controller specified by table 2.

4 Example of a Fuzzy Controller Hardware Implementation

Let us consider a demo procedure of a real fuzzy controller design as an analog hardware device. The description of the controller is taken from [9]. It provides controlling of a car seat and able to perform subtle attitude control without giving an unpleasant feeling to passengers.

The initial fuzzy controller specification is shown in table 3.

Table of specification. **Table 3**

V		ZR	PM	PL	PVL
X	*dX*				
ZR	*	ZR	ZR	ZR	ZR
RM	ZR	ZR	ZR	PS	PM
	PL	ZR	PS	PM	PM
RL	ZR	ZR	PS	PM	PM
	PL	ZR	PS	PL	PL

This table has three input variables: X – angle of steering wheel rotation, dX – derivative from X, and V – car velocity. Let linguistic values of the variables correspond to the voltages completely located in the interval 0–3.5V as it is shown in table 4.

Correspondence linguistic variable values to voltages. **Table 4**

X	ZR=0	RM=1.75V	RL=3.5V	
dX	ZR=0		PL=3.5V	
V	ZR=0	PM=(3.5/3)V	PL=(7/3)V	PVL=3.5V
Output	ZR=0	PS=(3.5/3)V	PM=(7/3)V	PL=3.5V

Let us split evenly the voltage interval 0 – 3.5V onto 7 logical levels, designate these levels with integer numbers from -3 to +3, and transform table 3 into table 5 substituting linguistic values of the variable with corresponding logical values.

Multi-valued logical function *F*. **Table 5**

X	*dX* \ *V*	-3	-1	1	3
-3	*	-3	-3	-3	-3
0	-3	-3	-3	-1	1
	3	-3	-1	1	1
3	-3	-3	-1	1	1
	3	-3	-1	3	3

For value combinations of the input variables, which are absent in the table 5 (i.e., for situations which are not defined by fuzzy rules), values of the output function can be supplementary defined up to any accepted values.

Now let us present the table 5 in the form of decomposition:

if $dX = -3(ZR)$ then $F = F_1(X,V)$ else

$$F = F_1(X,V) + \frac{3+dX}{6}(F_2(X,V) - F_1(X,V)).$$

This decomposition provides piece-linear approximation of *F* on the interval of *dX* changing from -3 to 3 and when *dX* = 3, $F = F_2(X,V)$. Definitions of the residual functions $F_1(\theta,V)$ and $F_2(\theta,V)$ are given in fig.9 and fig.10 respectively.

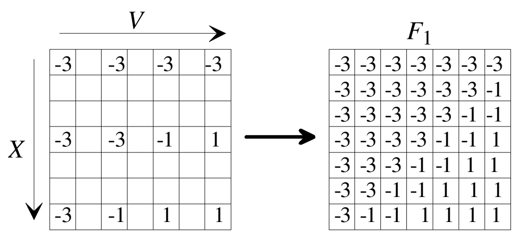

Figure 9. Description of the residual function $F_1(X,V)$.

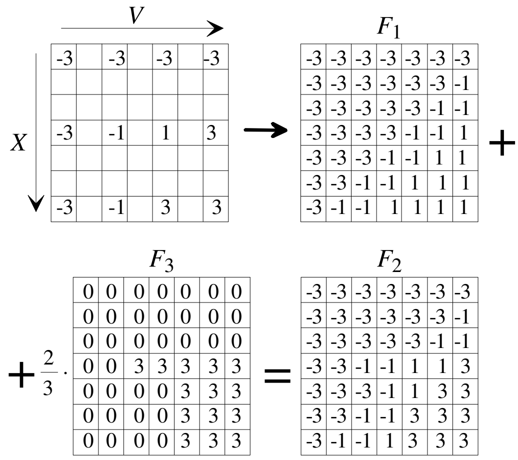

Figure 10. Description of the residual function $F_2(X,V)$.

As it is seen from fig.9, $F_1(X,V)$ can be supplementary defined up to a symmetrical function with respect to its arguments and reduced to the function of one variable $(X+V)$ with the graph shown in fig.11.

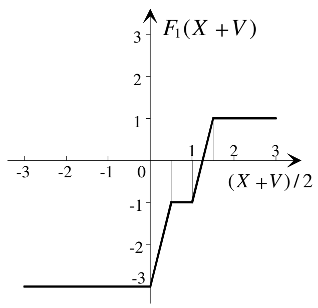

Figure 11. The function $F_1(X+V)$.

This function has two zones of changing the values and can be implemented on three amplifiers. Really

$$\beta_1 = S(6 \cdot X + 6 \cdot V - 3),$$

$$\beta_2 = S(6 \cdot X + 6 \cdot V - 15),$$

$$F_1 = S(\tfrac{1}{3}\beta_1 + \tfrac{1}{3}\beta_2 + 1),$$

where *S* is a function implemented by one summing amplifier.

From fig.10 it is possible to see that the residual function $F_2(X,V)$ can be presented as a sum of the same symmetrical function $F_1(X,V)$ and $\frac{2}{3}$ of the correcting function $F_3(X,V)$:

$$F_2(X,V) = F_1(X,V) + \tfrac{2}{3} \cdot F_3(X,V).$$

Let us split the matrix of the correcting function $F_3(X,V)$ on two sub-matrixes:

$$\overset{F_3}{\begin{vmatrix} 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&3&3&3&3&3 \\ 0&0&0&0&3&3&3 \\ 0&0&0&0&3&3&3 \\ 0&0&0&0&3&3&3 \end{vmatrix}} = \overset{F_4}{\begin{vmatrix} 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&3&3&3&3&3 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \end{vmatrix}} + \overset{F_5}{\begin{vmatrix} 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0 \\ 0&0&0&0&3&3&3 \\ 0&0&0&0&3&3&3 \\ 0&0&0&0&3&3&3 \end{vmatrix}}.$$

It is obvious that $F_3 = F_4 + F_5$. The function F_4 can be defined in the form of the rule 1:

If $(X = 0)\ \&\ (V \geq -1)$ then $F_4 = 3$ else $F_4 = 0$.

As it is not difficult to check that this rule can be implemented on five summing amplifiers:

$$\beta_3(X) = S(6X - 3),$$
$$\beta_4(X) = S(-6X - 3),$$
$$\beta_5(V) = S(-6V - 9),$$
$$\gamma_1(X,Y) = S[\tfrac{1}{2}(\beta_3(X) + \beta_4(X) + \beta_5(V) - 9)],$$
$$F_4(X,V) = S[\gamma_1(X,V) - 3].$$

The function F_5 is determined by the following rule 2:

If $(X \geq 1)\ \&\ (V \geq 1)$ then $F_5 = 3$ else $F_5 = 0$,

which can be implemented using four summing amplifiers:

$$\beta_6(X) = S(-6X + 3),$$
$$\beta_7(V) = S(6V - 3),$$
$$\gamma_2(X,V) = S[\tfrac{1}{2}(\beta_6(X) + 3) + \tfrac{1}{2}(\beta_7(V) + 3)],$$
$$F_5(X,V) = S[\gamma_2(X,V) + \tfrac{1}{2}(\beta_7(V) + 3)].$$

This implementation provides piecewise-linear coupling the function F_5 with the function F_4 by the coordinate X on the interval $\overline{0,1}$.

The output amplifiers of the circuits implementing the function F_4 and F_5 can be combined to get the implementation of the function F_3:

$$F_3(X,V) = F_4(X,V) + F_5(X,V) =$$
$$S(\gamma_1(X,V) - 3 + \gamma_2(X,V) + \tfrac{1}{2}(\beta_8(V) + 3)) =$$
$$S(\gamma_1(X,V) + \gamma_2(X,V) + \tfrac{1}{2}\beta_8(V) - \tfrac{3}{2}).$$

Now we are able to present the controller output value in the form:

$F = F_1(X + V) +$ (rule 3)

where rule 3 is

if $dX = 3$ then $\tfrac{2}{3}F_3(X,V)$ else $(dX = -3)$ 0.

The implementation of the rule 3 can has a view:

$$\beta_8 = S[\tfrac{1}{2}(dX - 3)], \quad -\beta_8 = S(\beta_8),$$
$$\gamma_3(X,V) = S(\beta_8 + F_3(X,Y)),$$
$$\gamma_4(X,V) = S(-\beta_8 + F_3(X,Y)),$$
$$S[\tfrac{2}{3}(\gamma_3(X,V) + \gamma_4(X,V) + F_3(X,V))].$$

This implementation demands five summing amplifiers and its output amplifier can be combined with the output amplifier of the F_1 implementation to produce the output signal of the controller:

$$F = F_1(X + V) +$$
$$S[\tfrac{2}{3}(\gamma_3(X,V) + \gamma_4(X,V) + F_3(X,V))] =$$
$$S[\tfrac{1}{3}(\beta_1 + \beta_2 + 3) + \tfrac{2}{3}(\gamma_3(X,V) +$$
$$\gamma_4(X,V) + F_3(X,V))].$$

The final controller implementation circuit is shown in fig.12.

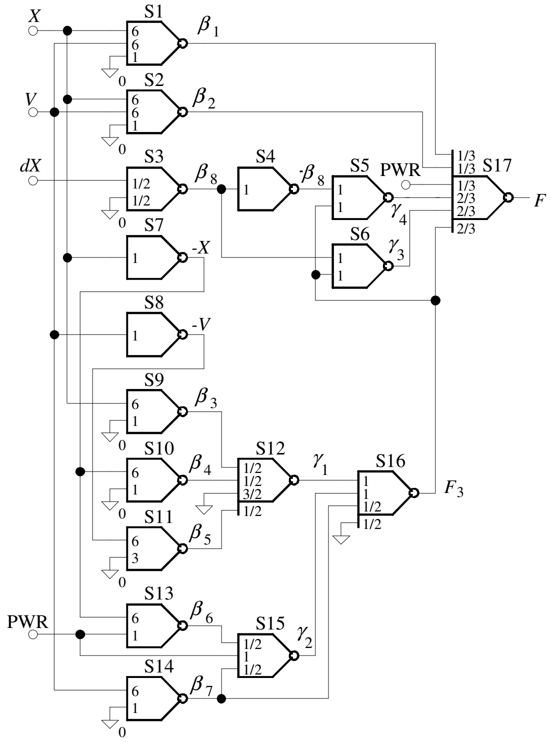

Figure 12. The controller implementation.

In this implementation the elements S7 and S8 are used for inverting signs of the arguments *X* and *V*.

Functioning of the controller has been checked with SPICE simulation (MSIM 8). MOSIS BSIM3v3.1, 7 level models of 0.4μm transistors has been used. The source voltage in the experiments was 3.5V.

Results of SPICE simulation of the circuit in fig.12 are represented in fig.13. In this figure the response surfaces in the coordinates *X, V* are shown for the cases *dX*=0V (fig.13,a) and *dX*=3.5V (fig.13,b).

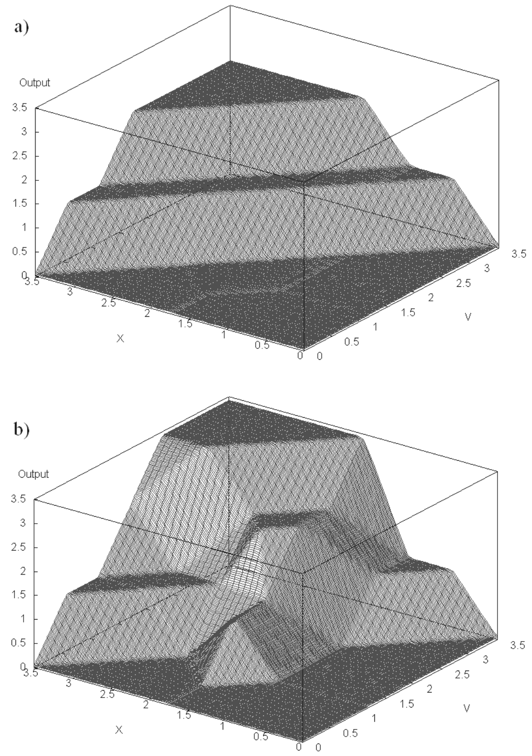

Figure 13. The response surfaces for the cases *dX*=0V (a) and *dX*=3.5V (b).

SPICE simulation results confirm logical correctness of the controller behavior.

5 Conclusions

In the above examples of controllers, push-pull summing amplifiers are used. The summing amplifier however can be of another type, e.g. differential type or any other types of operational amplifiers.

The proof of functional completeness shown in section 2 provides the possibility of implementing arbitrary function of multi-valued logic in the base of summing amplifiers. However, none mentioned above answers the question concerning the efficiency of such implementation and the techniques of synthesizing circuits in the offered base. Though the given examples show possible high efficiency and effectiveness of the implementation offered this is true only in regard to specific examples, chosen in special way.

Techniques of synthesizing fuzzy devices in the offered base and the problems of implementability under the conditions of real production should be resolved on further work stages.

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