Microcontroller Control of a Dynamic Plant Based on a Fuzzy Controller

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Abstract: The paper addresses the issue of constructing an adaptive control system for a dynamic plant using a fuzzy controller implemented as a Sugeno-type fuzzy system. For the technical implementation of the fuzzy controller, it is proposed to use an FPGA (field-programmable gate array) computing module, which is distinguished by its ability to integrate the control system with data collection into a single chip. This computing module is distinguished from known ones by its high computing power. The FPGA computing module in control systems allows it to operate with a significantly larger number of input and output streams in real-time data, and also, if necessary, the universality of the applied computing algorithms on one chip. Proposals for a method for selecting the bit depth of the fractional part of numbers, which makes it possible to ensure the necessary accuracy in the calculation of control signals. Adaptation of fuzzy controller parameters is carried out based on the “delta rule”, which makes it possible to significantly simplify the calculation of correction of fuzzy controller parameters and facilitate the implementation of the adaptation algorithm on various types of microcontrollers. To simplify the calculation of membership function parameters, it is proposed to use the min operation instead of the multiplication operation, which significantly reduces the calculation time of the transient process. As a dynamic plant, let's consider a DC motor. A comparative analysis of the proposed system of adaptive microcontroller control of a PI controller configured for optimal performance is presented.

1 INTRODUCTION

One of the ways to increase production productivity is to use modern energy-saving technologies to control technological plants [1]-[3]. The solution to this problem is directly related to the control of electric drives, which is the main executive element of the system [4]. Currently, DC motors with traditional linear PID controllers are widely used to control various technological equipment [5]-[9]. The most significant disadvantage of the above controllers implemented based on a microcontroller is their low performance [10]-[12]. For instance, if the progress of a technological process is controlled using 10-bit sensors and the number of words coming from two sensors is 1024*1024=1048576 words, then to select a control action, it is necessary to perform 20 million operations per unit of time [13].

It should be noted that as the number of controlled parameters increases, the performance of the system also decreases. These problems pose the task of selecting a microcontroller with a highly efficient computing module [14]-[16]. Modern electric drive control systems use controllers built based on a microcontroller using an FPGA computing module.

This circumstance is conditioned on several technical and economic factors, such as [17]-[19]:

- the ability to integrate a control (computing) data acquisition system into one chip (one chip - one solution);
- high computing power;
- relatively low cost of the device.

It should also be noted that currently, Verilog HDL/VHDL modeling methods and devices allow using them together with the MATLAB simulation package and, for instance, Xilinx System Generator for simulation and verification of developed algorithms [20], [21].

2 METHOD

The development of microcontroller control of the dynamic plants was carried out according to the following scheme:

- converting calculations of the control system from double to fixed point and analyzing the required accuracy for a given control regulation;
- synthesis of control algorithm in Verilog HDL/VHDL;
- mathematical modeling of the control system and analysis of results;
- compilation of the project for FPGA, verification, and analysis of the quality of operation of the developed control system.

To solve the problem of the synthesis of microcontroller control of a DC motor (DCM), an approach based on direct adaptive control is proposed. It should be noted that during DCM operation, stochastic changes in load, voltage supply, and motor current occur. Therefore, for adaptive control purposes, it is proposed to use the fuzzy control law in the form of the Sugeno model. Then the regulation law implemented in the microcontroller is represented as a fuzzy system of the Sugeno type [2], described by the formula:

$$u(x) = \frac{\sum_{k=1}^{M}\left(\coprod_{j=1}^{N} \mu_{\Lambda i}(x_j)\right)\cdot z_k}{\sum_{k=1}^{M}\left(\coprod_{j=1}^{N} \mu_{\Lambda i}(x_j)\right)}, \quad (1)$$

where x_j - variables values, u(x) - control signal generated by the microcontroller, $\mu_{\Lambda i}$- membership function, M - number of the fuzzy system rules, N - number of the fuzzy system inputs, Z_k - coefficients of the fuzzy system output. For phaseization, we choose a triangle-shaped membership function that is convenient for practical implementation and is described by the dependence

$$\mu_{\Lambda i}(x_j) = \max\left(\min\left(\frac{x_j - a_j^{(i)}}{b_j^{(i)} - a_j^{(i)}}, \frac{c_j^{(i)} - x_j}{c_j^{(i)} - b_j^{(i)}}, \right), 0\right).$$

To simplify the calculations of membership functions, division $b_j^{(i)} - a_j^{(i)}$ and $c_j^{(i)} - b_j^{(i)} c_j^{(i)} - b_j^{(i)}$ are replaced by multiplication by their reciprocals. The calculation of membership functions can be further simplified by choosing the coefficients a, b, c in the form a = 2m, m is the number of bits. Then the multiplication is replaced by a bit shift. This simplification was introduced in connection with the limited number of multiplication units in FPGA chips. It is known that the multiplication operation in calculating control actions significantly increases the speed of calculating normalised controls, i.e. computational costs. To solve this problem, it is proposed to replace the multiplication operation with the minmax operation, which does not affect the quality of control.

In this case, the fuzzy system is described by the following dependence:

$$u(x) = \sum_{k=1}^{M}\left(\min_{1\le j\le N}\left(\mu_{\Lambda i}(x_j)\right)\right)\cdot Z_k. \quad (2)$$

To change the fuzzy controller parameters, the deviation error between the actual motor speed and the desired speed, which is determined using a model of the desired dynamics, is used. The minimized quality functional is determined by the formula:

$$\varepsilon = \frac{1}{2}(\omega - \omega *)^2, \quad (3)$$

where ω, ω*- are the corresponding current and given values of neuron weight coefficients; ε - deviation error between the actual engine speed and the desired speed.

The formula for adapting the fuzzy controller parameters is the so-called “delta rule”, which is similar to the “steepest descent” method. To find the value of the correction coefficients, it is necessary to differentiate expression (3) according to the parameters of the fuzzy controller. As a result, we get:

$$Z_{i+1} = Z_i - \eta\frac{\partial\varepsilon}{\partial Z_i} = Z_i - \eta(w - w')\left(\min_{1\le j\le N}\left(\mu_{\Lambda i}(x_j)\right)\right),$$

where η is the learning speed of neurons.

The coefficient η > 0 plays the role of a weighting coefficient.

As can be seen, in the presented control law, there are no corrections to the parameters of the membership functions a, b, c. With this adaptation law, the influence of membership function parameters is relatively small compared to the influence of output layer Z parameters, which greatly simplifies the calculation of parameter corrections and facilitates the adaptation algorithm. To implement the proposed adaptation algorithm, an FPGA microcontroller was selected, allowing parallel organization of the LUT/DSP/BRAM operation calculation process. The FPGA platform is built on Xilinx Artix-7, with a clock frequency of 100 MHz, a sampling time of 50 µs, a fixed-point format of Q3.13 (16 bits), number of rules M = 9, number of inputs N = 2, training parameters η = 0.001÷0.01, resource usage: LUT = 3000÷5000, DSP=18÷25, BRAM=2÷4, controller latency≈100 ns and update frequency - 20 kHz.

The use of fixed-point calculations in an FPGA, in this case, is advisable because, firstly, floating point does not require more computing resources, and secondly, all the accuracy of the calculations will be offset by the quality and accuracy of the measured signals. In this regard, an analysis of the synthesized regulation system with fixed-point arithmetic was carried out.

When using a microcontroller as a control device, the most common method of transitioning from floating-point to integer calculations is to simply scale all signals by a factor k>>0, equal to the largest signal in the system, rounded to the nearest integer. A significant disadvantage of this method is the need to scale all coefficients and parameters of the system.

Another way is to set a certain precision (bit depth) for the integer and fractional parts of the number (Fig. 1). The number format is selected as, for instance, 32 bits (digits).

The number of integer digits is selected from the conditions of the maximum operating range of the number, and the number of fractional digits is selected from the requirements for calculation accuracy.

In general, a floating-point number is represented as:

$$\text{fixed point} = (-1)^{z} 2^{n} + 2^{-m} \quad .$$

where z, n, and m are integer numbers.

The 32-bit number is stored as an integer, and the decimal point is only used when converting from integer format to floating point format [4]. When multiplying, the number of fractional digits is doubled, but the least significant digits are discarded with a loss of precision. Another bit is used to remember the sign of the number. As a rule, an increase in the bit depth of numbers leads to an increase in requirements for the computing power of the chip and the volume of its communications.

3 RESULTS AND DISCUSSION

To substantiate the proposed approach, consider a microcontroller speed control of a DC motor built based on a fuzzy controller (Fig. 2). The motor has the following parameters: rated voltage: U_N = 20 V, rated speed: w_n=8360 1/min (875 rad/s), maximum torque: M_n= 26.7 mH×m. The model parameters are presented in Table 1.

Table 1: DC motor parameters.

Parameters of a DC motor		
L, Gn	R, Om	Cm, H×m/A
0.24/1000	2.32	23.4/1000
Parameters of a DC motor		
Cv, m×sec/rad	J, kg×m^2	
407/(2×π/60)/l000	10.3/(1000×104)	

The control scheme and structural scheme of the motor are shown in Figure 2.

Figure 3 shows the results of simplifying the structure of a fuzzy system using and without a normalization layer, as well as using the "AND" rule - multiplication by min operations. From the presented transient processes, we can conclude that refusal of normalization noticeably accelerates the transient process and increases over-regulation. Using the min operation instead of multiplication does not significantly affect the control error.

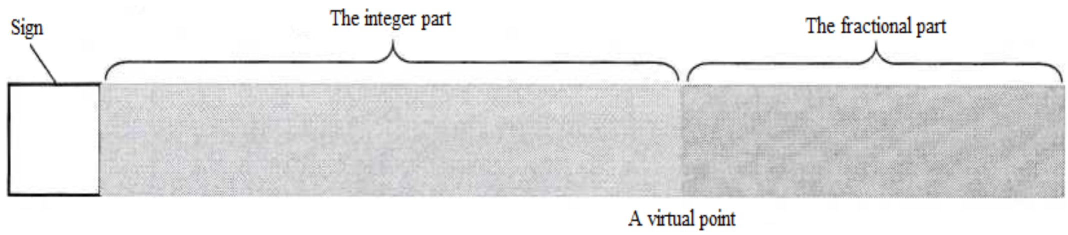

Figure 1: Representing a floating point number as an integer.

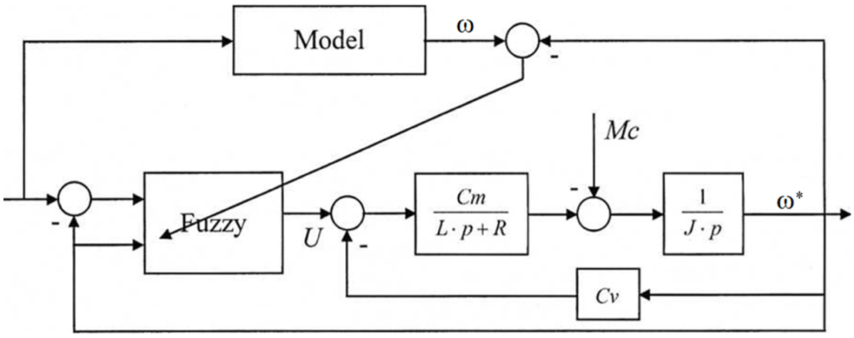

Figure 2: Structural scheme of the direct adaptive control system of a DC motor.

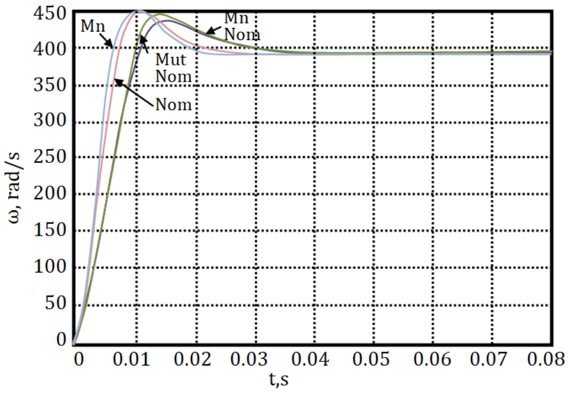

Figure 3: Transient processes of speed regulation during various operations of fuzzy rules.

As shown in Figure 4 graphs of transient processes when controlling a DC motor with a neuro-fuzzy regulator and a PI controller configured for optimal performance. On the left are graphs corresponding to the neuro-fuzzy controller. On the right are graphs of the transient process by PI control. As shown in our graphs corresponding to the absolute deviation of the current coordinate in a fixed point from the "ideal" process in numbers with a floating point. At a time of 25 ms/25 sec, the moment of inertia of the motor increases abruptly by 5 times.

From the test results presented in Figure 3, the simplifications introduced into neuro-fuzzy do not have a strong negative impact on the transient process of the regulated system.

At a time of 50 ms/50 sec, a load torque equal to the nominal one is applied - 0.0283 N·m.

The following designations are introduced in Figure 4: 1 transient process with a fixed-point of a total of 32 bits, and of these 8 bits for the fractional part when the moment of inertia of the motor changes; 3 transient process at a fixed-point is only 32 bits, and of these 4 bits are for the fractional part, without changing the moment of inertia of the motor; 4 transient process with a fixed-point is only 32 bits, and of these 4 bits are for the fractional part when the moment of inertia of the motor changes.

As can be seen from Figure 4, for acceptable control accuracy, it is enough to use 32-bit numbers, in which the fractional part must have at least 5 digits. As the bit depth of the fractional part increases, the accuracy sharply increases. If the fractional part has a bit depth of more than 8, the process is practically no different from calculations in floating-point. The oscillatory process of changing the speed deviation during neuro-fuzzy control is explained by the influence of the controller adaptation law. In addition, the neuro-fuzzy controller always strives to reduce the error, and in static mode, the deviation from the set value tends to zero, while in fixed point calculations, the PI controller has a static error when regulating the speed. In both regulators, acceptable regulation quality is achieved when the motor inertia moment changes. When using only 4 digits for the fractional part of numbers, the neuro-fuzzy controller operates with fluctuations, which are caused by errors in performing arithmetic operations. The PI controller still works without fluctuations since it requires significantly fewer calculations.

The next step in this direction is to adapt the developed approach for practical use in a wide range of industrial controllers.

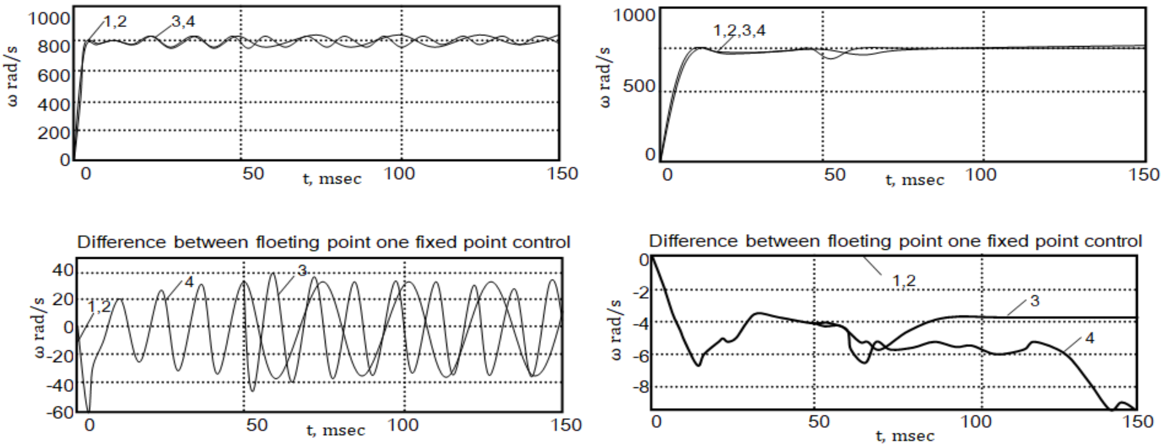

Figure 4: Transient process of regulating the speed of a DC motor with different levels of accuracy of number representation.

4 CONCLUSIONS

The paper presents the possibilities of building an adaptive control system based on a fuzzy controller, implemented in an FPGA computing module, which can integrate a control system with operations of collecting, storing, and processing information into one chip. Adaptation of fuzzy controller parameters is carried out based on the "delta rule", which makes it possible to significantly simplify the calculation of correction of fuzzy controller parameters and facilitate the implementation of the adaptation algorithm on various types of microcontrollers. To simplify the calculation of the membership function parameters, it is proposed to use the min operation instead of the multiplication operation, which will significantly increase the time for calculating the transient process. As a dynamic plant, let's consider a DC motor. A comparative analysis of the proposed system of adaptive microcontroller control of a PI controller configured for optimal performance is presented, together with an analysis of how the fractional-part bit width of fixed-point number representation affects control accuracy; the neuro-fuzzy controller demonstrated a faster, smoother transient response with lower deviation from the ideal floating-point trajectory than the PI controller under abrupt inertia and load-torque changes. The applications of FPGAs make it possible to implement complex control algorithms in an automated environment, which allows for preliminary modeling and ultimately obtaining effective, reliable, and relatively cheap means of controlling complex dynamic plants. The innovative approach of this study lies in the possibility of using fuzzy logic in microcontrollers to control DC motor in the event of random load changes.

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