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FPGA-Based Fuzzy Logic: Design and Applications – a Review

Nasri Sulaiman, Zeyad Assi Obaid, *Member, IACSIT,* M. H. Marhaban and M. N. Hamidon

Abstract— **A large numbers of fuzzy control applications with the physical systems require a real-time operation to interface high speed constraints; higher density programmable logic devices such as field programmable gate array (FPGA) can be used to integrate large amounts of logic in a single IC. This paper reviews the state of the art of FPGA with the focus on FPGA-based fuzzy logic controller. The paper starts with an overview of FPGA in order to get an idea about FPGA architecture, and followed by an explanation on the hardware implementation with both type analogue and digital implementation, a comparison between fuzzy and conventional controller also provided in this paper. A survey on fuzzy logic controller structure is highlighted in this article with the focus on FPGA-based design of fuzzy logic controller with different applications. Finally, we provided the simulation and experimental results form the literature and concluded the main differences between software-based systems with respect to FPGA-based systems, and the main features for FPGA technology and its real-time applications**.

Index Terms—**FPGA-based fuzzy logic, hardware implementation, Fuzzy logic controller, conventional controller, digital technique, analog technique.**

I. INTRODUCTION

Most of the fuzzy logic applications with the physical systems require a real-time operation to interface high speed constraints. The simple and usual way to implement these systems is to realize it as a software program on general purpose computers, these ways can not be considered as a suitable design solution. Higher density programmable logic device such as FPGA can be used to integrate large amounts of logic in a single IC. FPGA becomes one of the most successful of technologies for developing the systems which require a real time operation. For these systems [4], [8], [37], [39], FPGAs are more sufficient than the simple way because they can cover a much wider range of operating conditions. Semi-custom and full-custom application specific integrated circuit (ASIC) devices are also used for this purpose but FPGA provide additional flexibility: they can be used with tighter time-to-market schedules. FPGA places fixed logic cells on the wafer, and the FPGA designer constructs more Complex functions from these cells [11]. The term field Programmable highlights the customizing of the IC by the user, rather than by the foundry manufacturing the FPGA. Several researchers discussed the design of hardware systems. Numbers of these works were specialized in control application, and were aim to get better control responses, [40], [47]. FPGA are two dimensional arrays of logic blocks and flip-flops with an electrically programmable interconnection between logic blocks. The interconnections consist of electrically programmable switches which is why FPGA differs from Custom ICs, as Custom IC is programmed using integrated circuit fabrication technology to form metal interconnections between logic blocks. In an FPGA logic blocks are implemented using multiple level low fan in gates, which gives it a more compact design compared to an implementation with two-level AND-OR logic. FPGA provides its user a way to configure: The intersection between the logic blocks and the function of each logic block. Logic block of an FPGA can be configured in such a way that it can provide functionality as simple as that of transistor or as complex as that of a microprocessor. It can used to implement different combinations of combinational and sequential logic functions [28].

II. HARDWARE IMPLEMENTATION TECHNIQUES

The techniques used for hardware implementation include:

A. *Analog Techniques*

The variables in fuzzy systems are analog by nature. Thus, analog implementation eliminates the need for analog-to-digital and digital-to-analog conversions [13], [14]. The fuzzy systems also require massive parallelism, making analog circuits particularly suited for their implementation. Furthermore, the physical characteristics of transistors can be utilized in realizing the nonlinear functions required, whether it is a fuzzy operation, or a membership function. Analog implementations, however, have typically very restricted possibilities for programmability. Analog implementation techniques include voltage mode and current mode realizations, in addition to mixed mode (current and voltage) realizations. One difficult aspect of analog circuit implementations is devising a reliable analog memory module [12], [13].

B. *Digital Techniques*

Although fuzzy chips may have limited input/output capabilities, they have particularly useful applications in real-time control systems. Analog fuzzy values must be converted to binary digital signals. Analog-to-digital conversion can lead to quantization errors in both input

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Corresponding author, Zeyad Assi Obaid , is with the Department of Electrical & Electronic Engineering, Faculty of Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia.(Phone:0060173539328, Fax: +6086567099).

Nasri Sulaiman, M. H. Marhaban and M. N. Hamidon, with the Department of Electrical & Electronic Engineering, Faculty of Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia.

signals and membership values. Thus, decline in the fuzzy processing may occur if an insufficient number of bits are used to represent the analog signals. On the other hand, using a large number of bits can slow down the process. This is the trade-off between precision and speed. Fuzzy dedicated circuits are characterized by [13]:

- The number of inputs and outputs.
- The number and shapes of membership functions.
- Inference techniques including operators, consequences, and size of the premises.
- Defuzzification method.
- The number of fuzzy logic inferences per second, FLIPS.
- Physical size.
- Power consumption.
- Software available to support the design.

III. FUZZY VS. CONVENTIONAL CONTROL

In order to design a conventional controller for controlling a physical system, the mathematical model of the system is needed. A common form of the system model is differential equations for continuous-time systems or difference equations for discrete-time systems. Strictly speaking, all physical systems in existence are nonlinear. Unless physical insight and the laws of physics can be applied, establishing an accurate nonlinear model using measurement data and system identification methods is difficult in practice. Even if a relatively accurate model of a dynamic system can be developed, it is often too complex to use in controller development, especially for many conventional control design procedures that require restrictive assumptions for the plant (e.g., linearity) [22], [23].

As an alternative, fuzzy control provides a formal methodology for representing, and implementing a human's heuristic knowledge about how to control a system, which may provide a new paradigm for nonlinear systems. Fuzzy controller is unique in its ability to utilize both qualitative and quantitative information. Qualitative information is gathered not only from the expert operator strategy, but also from the common knowledge [22], [23]. Although much of the opposition to fuzzy logic is based on misconceptions, fuzzy control is not a cure-all. Fuzzy control should not be employed if the system to be controlled is linear, regardless of the availability of its model. PID control and various other types of linear controllers can effectively solve the control problem with significantly less effort, time, and cost. In summary, PID control should be tried first whenever possible [22].

The benefits of fuzzy controllers could be summarized as follows:

1. Fuzzy controllers are more robust than PID controllers because they can cover a much wider range of operating conditions than PID can, and can operate with noise and disturbances of different nature.
2. Developing a fuzzy controller is cheaper than developing a model-based or other controller to do the same thing.
3. Fuzzy controllers are customizable, since it is easier to understand and modify their rule, which not only use a human operator's strategy, but also are expressed in natural linguistic terms.
4. It is easy to learn how fuzzy controllers operate and how to design and apply them to a concrete application.

It is also worth to notice that fuzzy logic can be blended with conventional control techniques. This means that fuzzy system does not necessarily replace conventional control methods. In many cases fuzzy systems augment them and simplify their implementation [12], [24].

IV. STRUCTURE OF FUZZY LOGIC CONTROLLER

Fuzzy logic has rapidly become one of the most successful of today's technologies for developing sophisticated control systems. With its aid, complex requirements may be implemented in amazingly simple, easily maintained, and inexpensive controllers [20]. Fuzzy control use only a small portion of the fuzzy mathematics that is available, this portion is also mathematically quite simple and conceptually easy to understand. In this chapter, we introduce some essential concepts, terminology, and arithmetic of fuzzy sets and fuzzy logic. The fuzzy controller, (as explained in Fig. 1), have four main components:

- The Rule-Base holds the knowledge, in the form of a set of rules, of how best to control the system.
- The Inference Mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.
- The Fuzzification Interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base. And
- The Defuzzification Interface converts the conclusions reached by the inference mechanism into the inputs to the plant [23], [25].

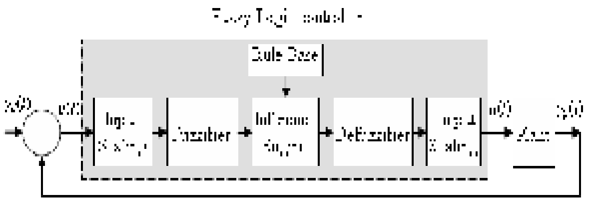


Fig. 1: Typical Fuzzy Controller Structure.

V. FPGA-BASED FUZZY LOGIC CONTROLLER

There are several types of control systems that use FLC as an essential system component. The majority of applications during the past two decades belong to the class of PID fuzzy controllers. These fuzzy controllers can be further classified into three types: the direct action (DA) type, the gain scheduling (GS) type and a combination of DA and GS types. The majority of PID fuzzy applications belong to the DA type; here the PID fuzzy controller is placed within the feedback control loop, and computes the PID actions through fuzzy inference. In GS type controllers, fuzzy inference is used to compute the individual PID gains [19], [26], [27]. The simplest and most usual way to implement a fuzzy controller is to realize it as a computer program on a general purpose computer. However, a large number of fuzzy control applications require a real-time operation to interface high-speed Constraints. Software implementation of fuzzy logic on general purpose computers can not be considered as a suitable design solution for this type of application, in such cases, design specifications can be matched by specialized fuzzy processors. Higher density programmable logic devices such as FPGA can be used to integrate large amounts of logic in a single IC [30]-[36]. Semi-custom and full-custom application specific integrated circuit (ASIC) devices are also used for this purpose but FPGA provide additional flexibility: they can be used with tighter time-to-market schedules. The Field-Programmable Gate Array (FPGA) places fixed logic cell son the wafer, and the FPGA designer constructs more complex functions from these cells. The term field programmable highlights the customizing of the IC by the user, rather than by the foundry manufacturing the FPGA [1], [45]-[47].

The authors in [3] designed a high-performance digital servo system built on FPGA, the proposed a hardware design scheme of a direct torque control (DTC) with low speed permanent magnet synchronous motor (PMSM). They used a Verilog language to describe The DTC strategy of PMSM. Because of the large torque ripples in low speed PMSM, they used fuzzy logic controller instead of the hysterics controller in a conventional PMSM DTC [3]. Fig. 2 shows the structure of the permanent magnet synchronous motor direct torque control system.

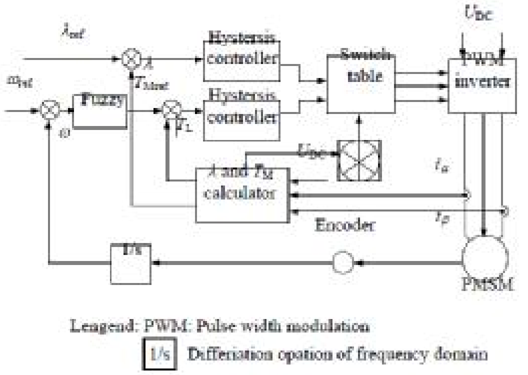


Fig. 2: The structure of the permanent magnet synchronous motor direct torque control system [3].

Other methods was proposed in [29], they divided the FLC into many temporally independent functional modules, and they implement each module on the FLC automatic design and implementation system, and this method is considered as an integrated development environment for performing many subtasks. Each implemented module forms a downloadable hardware object that is ready to configure the FPGA chip. Then, the FPGA chip is consequently reconfigured with one module at a time by using the run-time reconfiguration method. This implementation method is effective when a single FPGA chip cannot fit the FLC due to the limited size of its constituent cells [29].

Other approach used in [30] I implement fuzzy systems on FPGA which uses weighted average concept to keep the fuzzy lookup table small, yet the input sizes can be large. They implemented this design by using three or four most significant bits of each input in order to determine the address for the lookup table; fig. 3 shows the block diagram of the proposed fuzzy controller [30].

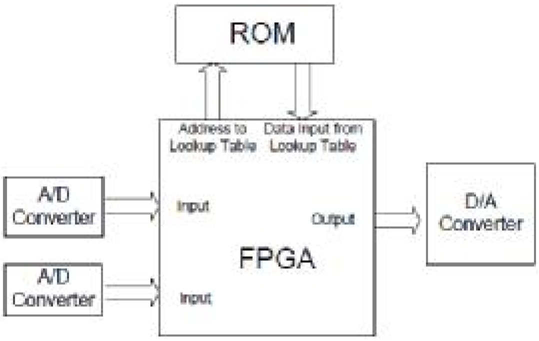


Fig. 3: Block diagram of fuzzy control board with FPGA [30].

And also the same way for FPGA-based implementations was proposed in [31], and this design was used to control variable speed generators, and this design has advantage of consisting of diesel engine, synchronous generator, power converter and fuzzy controller, are underlined. The figure below shows the fuzzy controller for diesel engine stands alone generator system which proposed in [31].

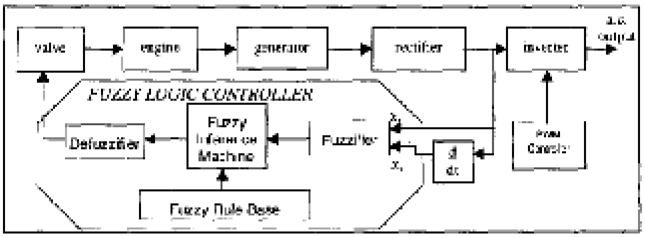


Fig. 4: Fuzzy controller for diesel engine stands alone generator system [31].

The authors in [32] proposed a fuzzy PID controller, which is designed on FPGA in order to use it for industrial process, the reason o fuzzy logic is to tune the PID parameters by using again scheduling method; fig. 5 shows the process within digital PID processor [32].

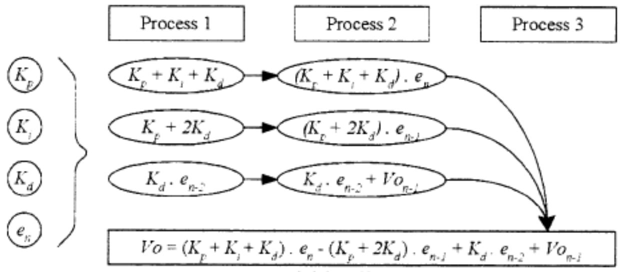


Fig. 5: The process within digital PID processor [32].

To perform some of the problematic operations needed in a fuzzy logic controller, the authors in [33] proposed other design method using techniques from Digital Signal Processing. The advantage of these techniques to enabled the development of circuits which are not only compact but also scalable; so that, when the accuracy of the controller or the number of inputs or membership functions is increased, do not suffer as high a rate of increase of the use of resources as for conventional circuits. And also they mainly report the development of the rule evaluation circuits [33]. The same way to design FPGA based fuzzy logic controller for electrical vehicle was proposed in [34] in order to control the speed of the motor, which in turn controls the vehicle dynamics to run the vehicle. So, the main aim is this work is to determine the motor speed which drives the vehicle, the parameters such as acceleration, braking, energy status, gear and terrain are considered, Fig. 6 shows the Block Diagram of the controller with FPGA proposed in [34].

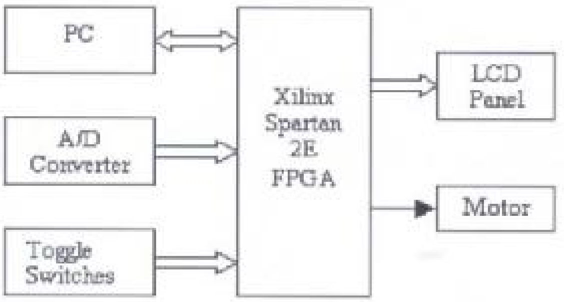


Fig. 6: Block Diagram of the controller with FPGA [34].

Barriga et al. in [35] are presented the modeling and implementation of fuzzy systems based on FPGA, they analyze different approaches for implementations of fuzzy systems on FPGA in order to characterize them in terms of area and speed, and also the use of specific processing architectures implemented on FPGAs presents as main advantages a good ‘‘cost-performance’’ ratio and an acceptably short development time [35]. A method to design of a Very High Speed Fuzzy Processor by VHDL Language presented by Gabrielli et al. in [36], The VHDL, as particular HDL is explained in some applications. In fact to present a first release digital fuzzy processor designed by means of the old Cadence Edge package from front-end schematic entry till the final layout design, in comparison to its VHDL re-design [36]. Other method to implement an embedded nonlinear fuzzy controller into an FPGA was presented in [37], by this flexible architecture, we can allows implementation which can be easily tuned through the use of the Simple Tuning Algorithm (STA) without a controller reference model, this design was developed using VHDL, and it was tested in soft real time using Xilinx System Generator and Simulink before the final implementation into the FPGA, fig. 7 shows the Simulink model used to achieve the soft real time application of controlling the speed of the DC motor proposed in [37].

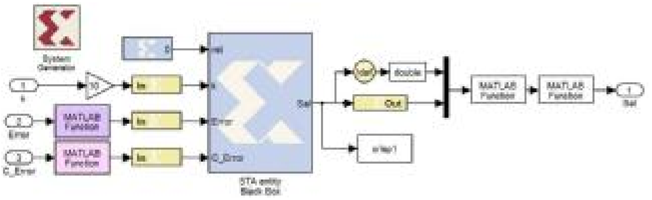


Fig. 7: Simulink model used to achieve the soft real time application of controlling the speed of the DC motor [37].

Other approach is proposed in [2] for the design and implementation of fuzzy traffic controllers using FPGAs. The focus of this study is to develop an effective traffic signaling strategy to be implemented at a typical intersection with four approaches, which involves VHDL-based logic synthesis and the use of state diagrams with a VHDL backend for graphical design description, the Fuzzifier and the Defuzzifier process of the fuzzy controller also described in VHDL and The fuzzy rule base for the controller is described using the state diagrams. The fuzzy inference is implemented using MATLAB code. The output of the MATLAB program is stored in a ROM for use in the VHDL code. Once VHDL code is obtained then the hardware is implemented using the UP1 Education board. After the design was tested by using UP1 board the next step was to design a printed circuit board for this system. This was done by using Portal Design Explorer where the input to the circuit board comes from traffic sensors in the field and the output of the circuit board is given to the traffic controller [2]. The authors in [6] presented as Description to the validation of five dispatching algorithms for elevator systems that were implemented on Spartan 3 FPGA-based boards in an integrated approach reducing the area and improving performance. Elevator systems are administrated by an elevator group control system (EGCS) and micro-processed sub-systems implementing a local control system (LCS) for each elevator. The overall system is composed of several LCS, which implement the dispatching algorithms, an RS485- based network and a virtual environment called virtual elevator interface system (VEI), which includes a simulator/monitoring system and an EGCS-based on fuzzy logic (FEGCS). The FEGCS runs on a PC and, under different traffic situations, determines the best algorithm to be run in each LCS in order to reduce the user waiting time and the power consumption as shown in fig. 8 [6].

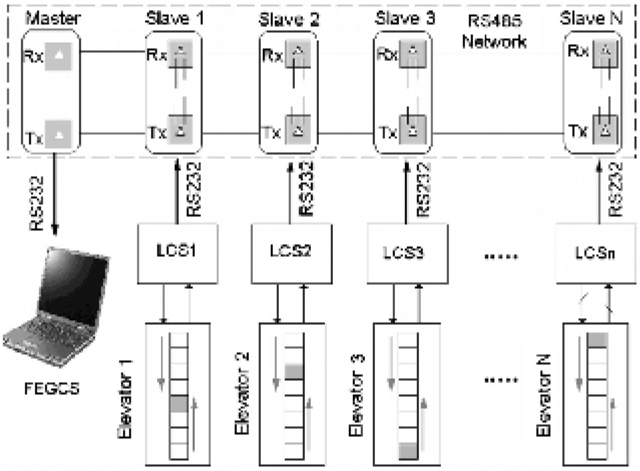


Fig. 8: The elevator control environment [6].

The novelty of this approach is that the LCSs are capable to run different dispatching algorithms independently, that are suitable for specific passenger traffic situations, while the FEGCS only must determine the best algorithm to be run in each LCS. The VEI allows the designer to test and validate in a flexible way the algorithm performance for different traffic situations, the figure below shows the Behavior of the five implemented dispatching algorithms proposed in [6].

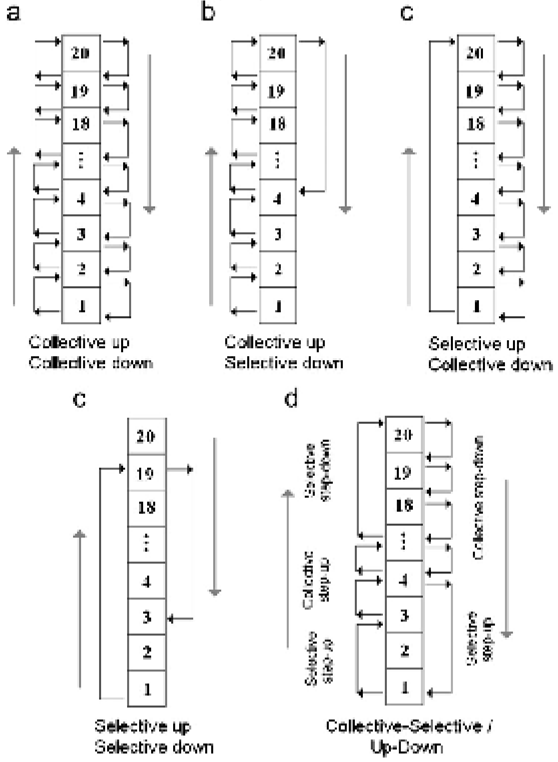
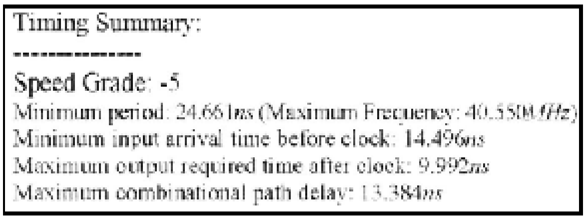


Fig. 9: Behavior of the five implemented dispatching algorithms [6].

VI. SIMULATION RESULTS

The fabricated process by applying fuzzy PID controller based on FPGA for process control proposed in [32] is verified by simulation, which uses the application program MODELSIM. The simulation of PID- fuzzy processor is to observe the changing of the parameters, from these simulation results, this processor can execute at maximum frequency 40.55 *MH* with one action using 85 clock cycles, therefore execute times about 24.661 *nsec* * 85 = 2.096 *μsec* per action, timing summary as shown in the figure below [32].



```
Timing Summary:
---------------
Speed Grade: -5
Minimum period: 24.661ns (Maximum Frequency: 40.550MHz)
Minimum input arrival time before clock: 14.496ns
Maximum output required time after clock: 9.992ns
Maximum combinational path delay: 13.384ns
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Fig. 10: Timing summary of the simulation results [32].

A novel approach to implement the fuzzy logic controller for speed control of electric vehicle by using FPGA proposed in [34]. The feedback from the motor is measured through CRO as shown in fig. 11. From the figure, it is inferred that it took 41.4ms to complete one revolution. Now in this condition, the motor is running at the speed of 1450rpm. By using this controller, the motor has been controlled to go at the maximum speed of 2127rpm for smooth terrain, 1725rpm for rough terrain, 1345rpm for uphill terrain and 1161rpm for downhill terrain [34].

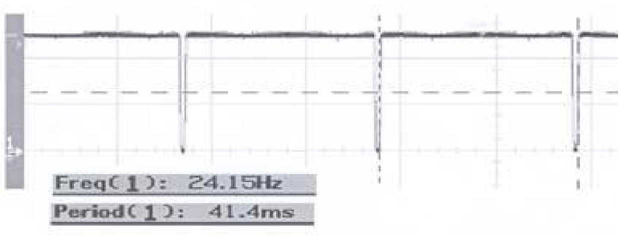


Fig. 11: Pulses from the motor for 65% duty cycle input [34].

The authors in [35] proposed Modeling and implementation of fuzzy systems based on VHDL, The different synthesis facilities provided by the Xfuzzy design environment for the implementation of programmable fuzzy systems, which take advantage of the available resources in the current FPGA families, Surfaces in Fig. 12 show the functions approximated by the different rule bases. These Results allow us to compare realizations of systems with different complexity and precision. Initial rule bases were adjusted with the tuning facilities provided by Xfuzzy, thus obtaining plain rule bases with 9, 25, 49, and 81 rules, respectively [35].

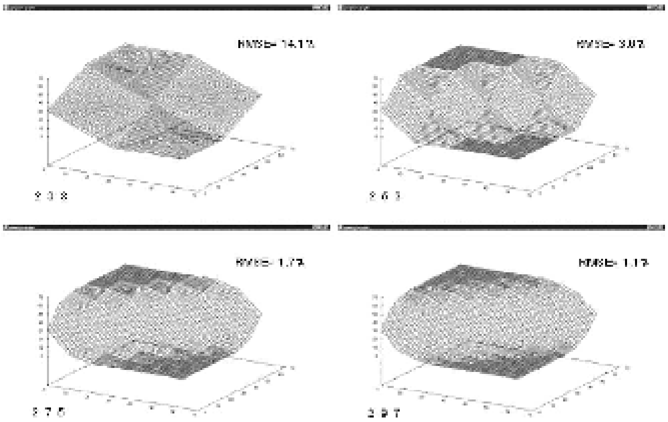


Fig. 12: Function surface (Eq. (3)) using 3, 5, 7 and 9 membership functions for antecedents [35].

Fig. 13 shows some implementation results on Spartan2E devices. Comparing the obtained values shows a reduction in terms of hardware resources and maximum delay when the rule number is compacted using the connective or and linguistic hedges [35].

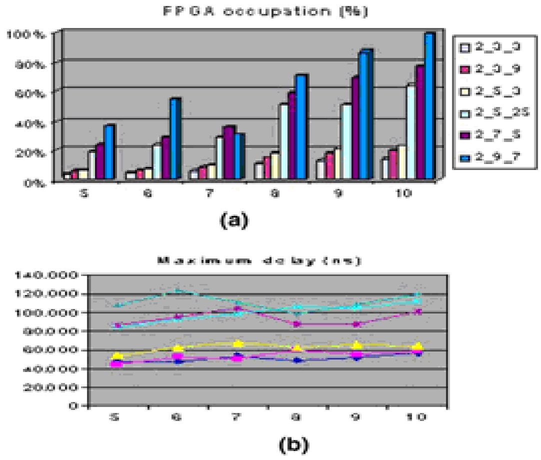


Fig. 13: FPGA occupation and maximum delay for rule base with different number of inputs_MFs_rules [35].

As an example, Fig. 14 illustrates that, for the particular case used in the text, the use of a specific architecture is advantageous when the required precision is greater than 8 bits [35].

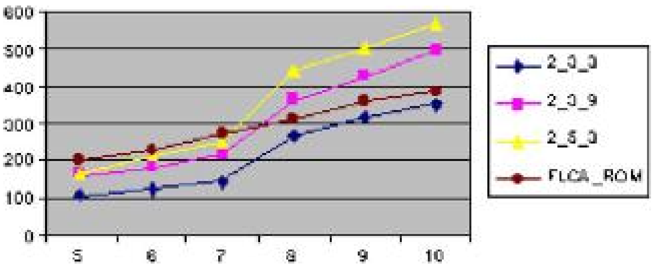
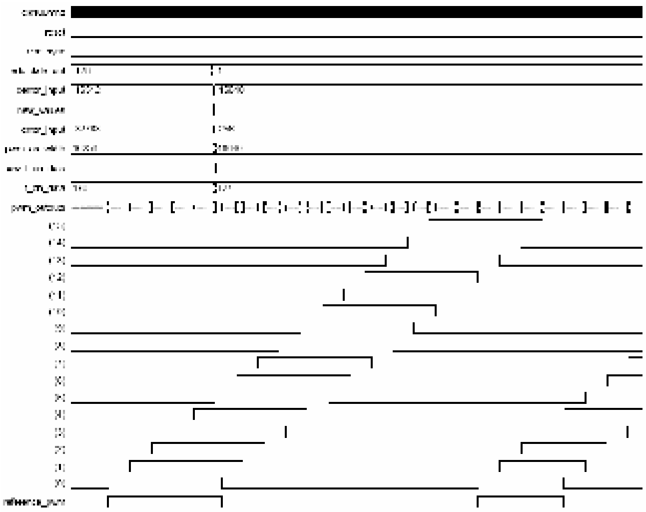


Fig. 14: Comparison of the results obtained by the behavioral and structural approaches [35].

FPGA-Based fuzzy logic controller for Automobile DC-DC Converters presented in [38], the design implemented in a Spartan 3 FPGA to achieve a real-time controller, in fig. 15 it is shown a simulation of the whole proposed system, where the final sixteen PWM shifted outputs to the DC-DC converter are presented [38].



Fig, 15: Timing simulation of the PWM outputs behavior [38].

And for industrial application a description of FPGA realization of a Fuzzy Temperature Controller (FTC) using VHDL intended and described in [39], Successful timing and functional simulations are carried out to verify the correct functionality of the algorithm. The operating frequency of the FTC chip is 5MHz with a critical path of 199.3ns. The waveform in Fig. 16 shows the values of the inputs and the corresponding output in hex form at the various instances determined by the stimuli in the test bench which proposed in [39].

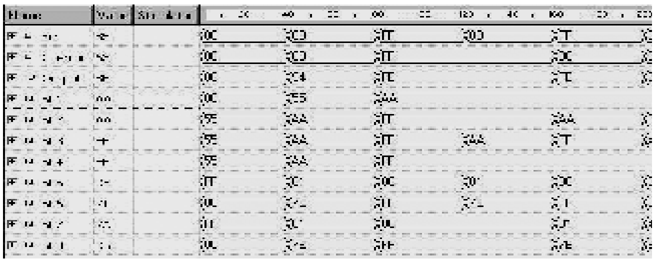


Fig. 16: Waveform of functional simulation of the FTC [39].

The same test stimuli are used for timing simulation taking into account the propagation delay. In addition, the simulation at this stage is performed upon nodes that are synthesizable. Slice of the timing waveform is shown in the Fig. 17 [39].

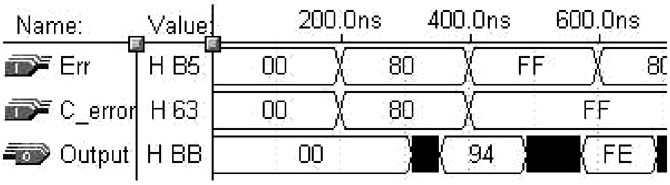
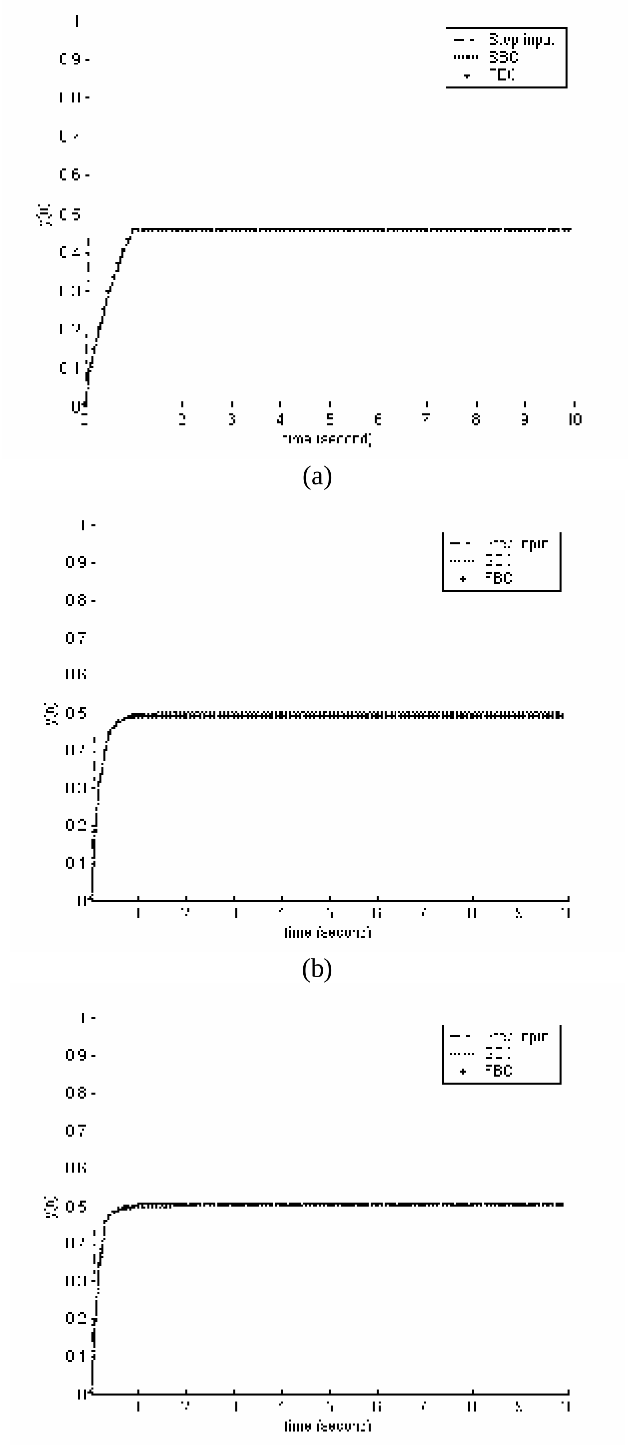


Fig. 17: Waveform of Timing Simulation of the FTC [39].

The design of PID-like fuzzy logic controller (PIDFLC) on FPGA device was proposed in [40]. The design utilizes 1394 slices of the target FPGA, and is able to produce an output at 0.421 μsec with maximum frequency of 40.295 MHz. The simulation results by apply this controller on linear systems were compared with simulation results of a similar system that uses a software-based controller, It is noticeable that some responses in fig. 18, have large steady state error (ess) and/or slow response (long rise time (tr)). Here we should emphasize that the aim of this test is to find to which extent the FBC responses are close to SBC responses, and not to find how to tune a PIDFLC to get better response [40].



(a)

(b)

(c)

Fig. 18: First order plant controlled by (a) PDFLC (b) PIFLC (c) PIDFLC [40].

Kartika in [41] presented FPGA application as irrigation controller with fuzzy logic method to make plants or crop healthy growth; it must have to control the irrigation. The signal output of the controller is Pulse Width Modulation signal, which will be used to drive irrigation control valve. Implementation of this design needs 24 I/O pins and 279 CLBs. The implementation of fuzzy logic controller needs 139 CLBs, so it fits in a single XS40-005XL Board, The pulse width output function is implemented by comparing the linear output signal to a ramp signal. If the linear output signal is less than ramp signal, the pulse output will be low. But, if the ramp signal is greater than linear output signal, then the pulse will be high. Fig. 19 shows how to form PWM signal [41].

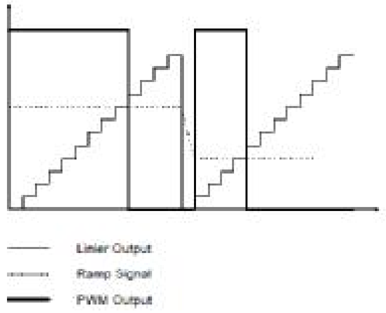


Fig. 19: The former of PWM signal [41].

The authors in [7] report on the implementation of intelligent fuzzy controllers for Internet traffic using an FPGA based prototyping platform. The focus is on the implementation results for FIM modules as they are the key component with higher operational requirements. Prototypes have been implemented on a Xilinx Spartan III FPGA, xc3s1500-fg456-5 device (1.5 millions of equivalent gates) included in the development board employed, an AvNet ADSXLX-SP3-EVL1500 [7]. The development and control model, etc. These algorithms depend upon the accuracy implementation of a multilayered fuzzy controller on an of the mathematical model of the robot and small errors in the FPGA for the navigational control of an autonomous model result in unsatisfactory navigational control of an autonomous mobile robot (AMR)was presented in [9]. The multilayered fuzzy controller was successfully implemented on FPGA and the results obtained similarly to other by simulation using FLASH. The simulation results for PD layer are shown in fig. 20, where the robot is shown to be in a passage [9].

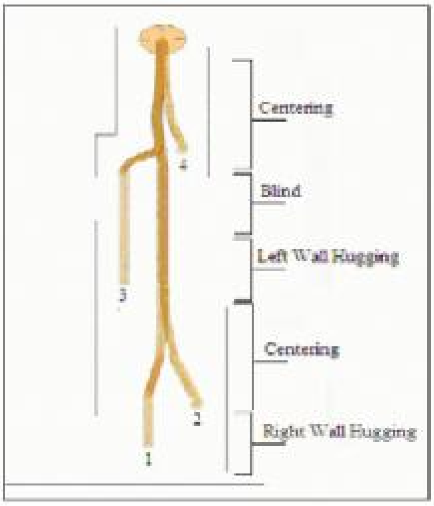


Fig. 20: Simulation results for PD Layer [9].

VII. EXPERIMENTAL RESULTS

Experimental results of A novel fuzzy logic direct torque controller for a permanent magnet synchronous motor with a field programmable gate array indicate that the fuzzy controller can provide a controllable speed at 20 r/min and torque at 330 N m with satisfactory dynamic and static performance. Those results show that this new control strategy decreases the torque ripple drastically and enhances control performance as shown in fig. 21 to fig. 23 [3].

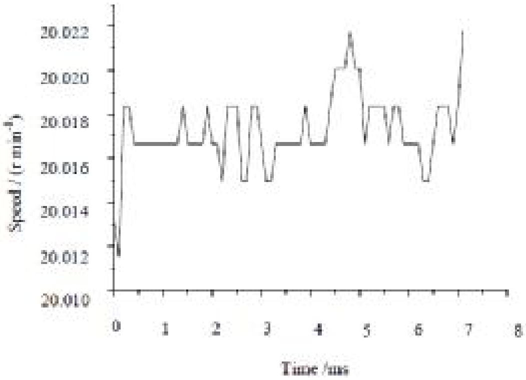


Fig. 21: Steady speed performance of permanent magnet synchronous motor direct torque control systems [3].

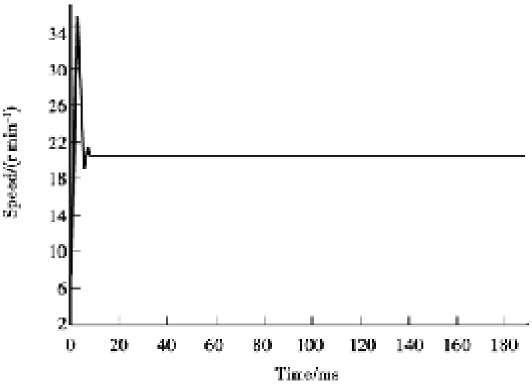


Fig. 22: Dynamic speed response of permanent magnet synchronous motor direct torque control System [3].

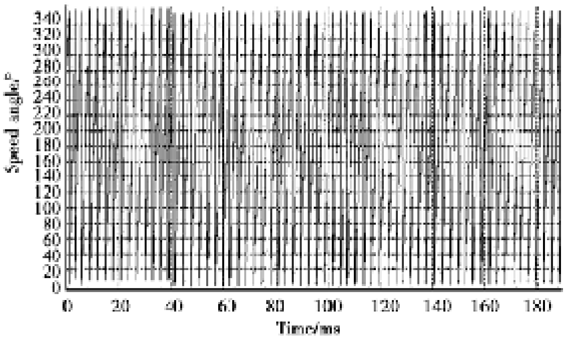
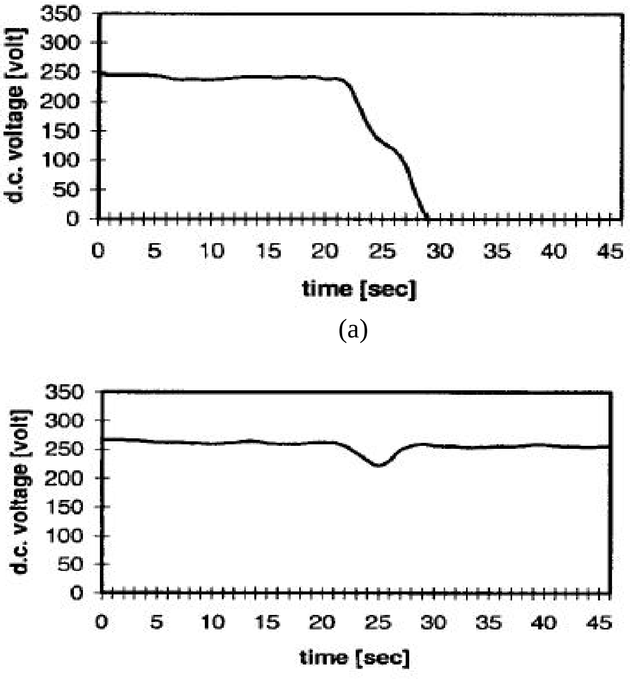


Fig. 23: Rotor position response of permanent magnet synchronous motor direct torque control system [3].

The experimental result for FPGA-based fuzzy controller applied with variable speed generator proved the correct operation of the systems. Fig. 24 shows voltage response with & without fuzzy controller in the design proposed in [31].



(a)

(b)

Fig. 24: (a): voltage response without fuzzy controller, (b): voltage response with fuzzy controller [31].

And also for applying of FPGA-Based Controller for Smart Induction Motor Design using an adaptive fuzzy neural network controller algorithm to control the induction motor, Fig. 25 describes the design of the proposed FPGA-based smart induction motor which proposed in [42].

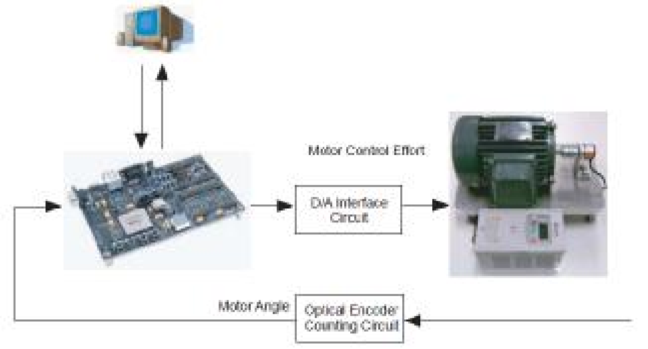


Fig. 25: FPGA-based smart induction motor controller [42].

The hardware circuit includes a frequency divider (Divider), induction motor angle counting module (Theta-Acc), and two rows of digital-to-analog converter (DAC) modules (DAC_1, DAC_2). The software is the Nios II embedded processor (Nios II CPU). The following figure shows the Hardware of FPGA Induction Motor Control System Block Diagram proposed in [42].

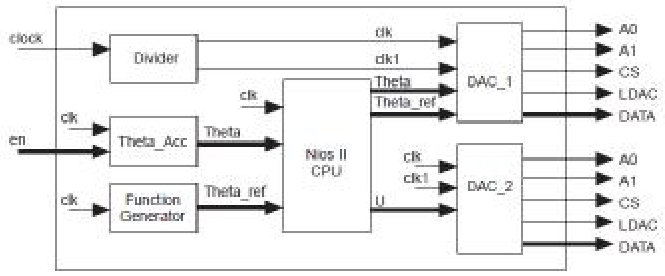


Fig. 26: Hardware of FPGA Induction Motor Control System Block Diagram [43].

The design’s peripheral circuit, as shown in Fig. 27, contains an optical encoder count circuit and two groups of D/A signal circuits with adjustable output voltage. The entire induction motor positioning control experiment environment is shown in Fig. 28 [42].

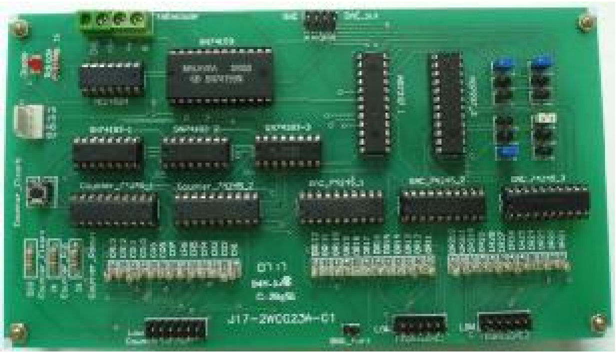


Fig. 27: Peripheral Hardware Printed Circuit Board [42].

Fig. 28: FPGA-Based Induction Motor Smart Control System Experiment Environment [42].

Experimental results of Simple Tuned Fuzzy Controller Embedded into an FPGA which proposed in [37] show that the fuzzy controller works for different tuning values, fig. 29 shows the main HW and SW components involved in the speed motor control application using a FInc controller embedded into an FPGA, which presented in [37].

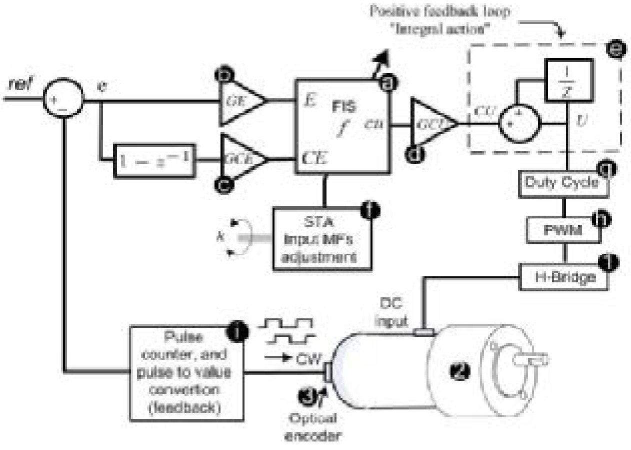


Fig. 29: Main HW and SW components involved in the speed motor control application using a FInc controller embedded into an FPGA [37].

Two experimental Simulink models to test the FInc and the STA working together in the speed motor control application were created. For the first module, Fig. 30 shows the control surface using the original MFs (k=0.5), Fig. 31 shows how the surface change with k equals to 0.7, and Fig. 32 shows the surface for k=0.9. For the second module, Fig. 33 shows the system response for several k values; in this figure, the faster response without overshoot is obtained using a k value of 0.9 [37].

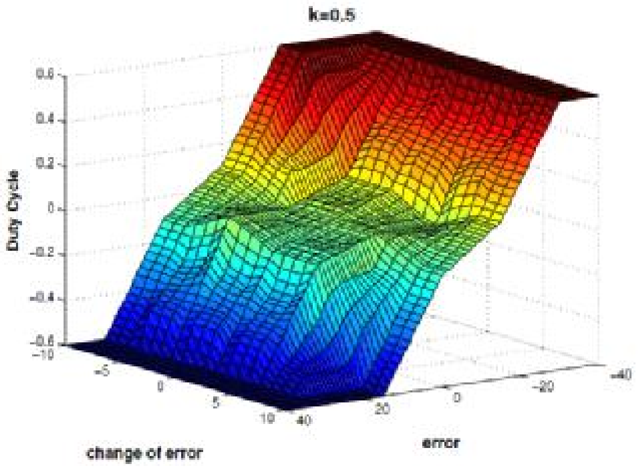


Fig. 30: Control surface using the original MFs; i.e., for k=0.5 [37].

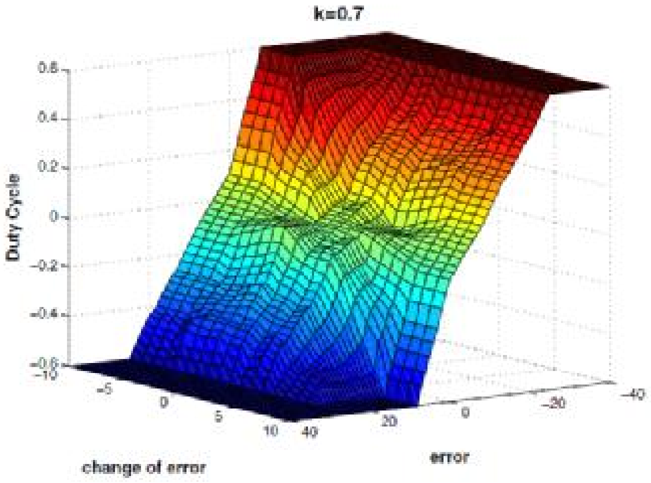


Fig. 31: Control surface for k=0.7 [37].

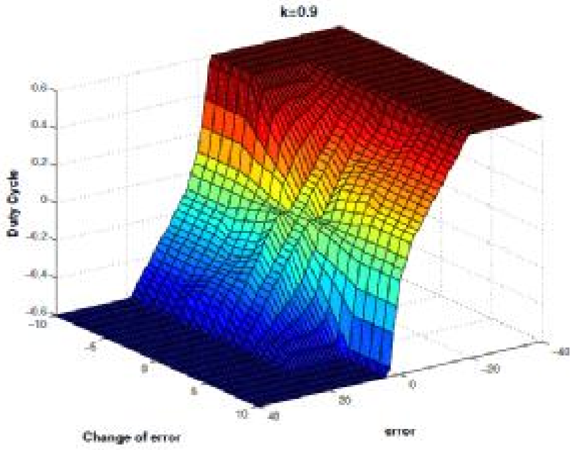


Fig. 32: Control surface for k=0.9 [37].

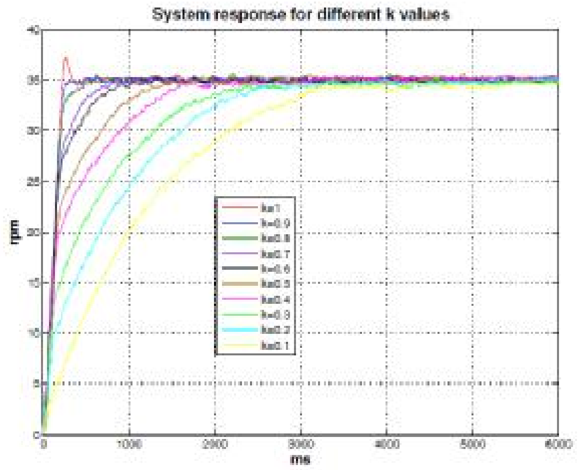


Fig. 33: System response for several k values [37].

The realization of embedded fuzzy control systems for planning the motion of autonomous mobile robots is presented in [5]. The development of the controllers is carried out by means of a reconfigurable platform based on FPGAs, [5]. When a constrained space is considered, the diagonal parking problem becomes more complex, because the driving direction (backward or forward) and the magnitude of the speed have also to be controlled in order to avoid collisions. Our proposal to solve this problem is a hierarchical FIM, composed by six knowledge bases, five inputs and four outputs [5]. A design methodology for fuzzy logic-based control systems is also presented in [10]. The methodology employs hardware/software co design techniques according to an 'apriori' partition of the tasks assigned to the selected components. Experimental results from an actual control application validate the efficiency of this methodology [10]. The above described methodology has been applied in the design of a level controller for a dosage system. As shown in Fig. 34-a, the control system prototyping was carried by using an XS40-005XL board from XESS Corporation [17] mounted on a board that also includes the A/D and D/A data converters together with the signal conditioning circuitry (Fig. 34-b), The software implementation in the 8031 was performed by using several development tools available for the MCS-51 family. The code downloaded to the microcontroller covers the typical tasks of a control cycle (acquisition and preprocessing, communication with the inference engine, post processing and output generation), and includes several interrupt service routines as well as routines to allow communication with a PC in order to evaluate the system performance (Fig. 34-c) [10].

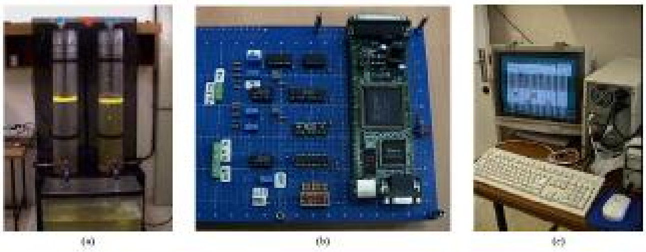


Figure 34: Experimental set up: a) Dosage system. b) Control system implementation. c) Development system [10].

Fig. 35: Illustrates how the liquid levels of the two tanks follow different target positions (dashed lines) with the typical ripple caused by the liquid dropping [10].

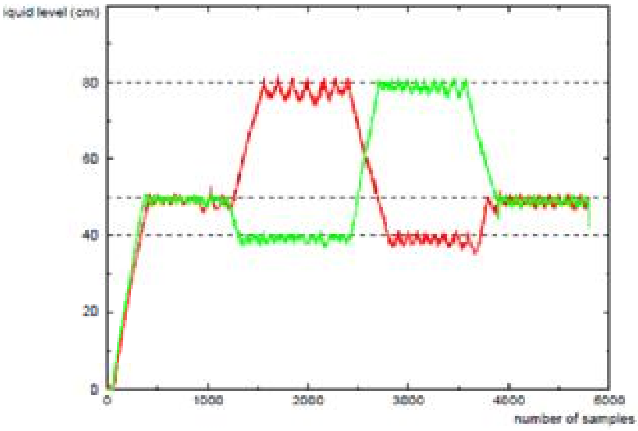
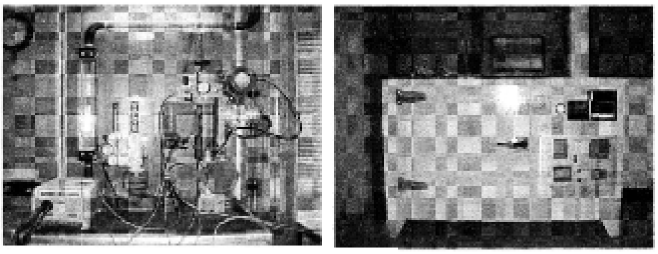


Fig. 35: Experimental results [10].

The timing Summary obtained by applying fuzzy PID controller based on FPGA proposed in [32] show that the maximum speed of the controller is about 2.1 µs per action at 40.550 MHz. From the experimental results of the level and temperature control, the fuzzy-PID controller has achieved and shown the better performance than standard PID controller E50AK which is automatic tunable parameter system. Fig. 36 shows the photograph of the experimental equipment which used in [32].



(a) (b)

Figure 36: (a) Equipment of the level process, (b) Equipment of the temperature process [32].

VIII. CONCLUSION

From this review, the authors focus and at most they preferred to implement these applications using FPGA, to make use of FPGA technology features (small device size, high speed, low coast, and short time to market). A control algorithm, when implemented in an FPGA, can have a very short execution time due to the high degree of parallelism of its architecture. At the same time, the constraints imposed by the power electronic components imply a sampling period that is, for many applications, much higher than the execution time. The resulting "wasted time" could be advantageously employed. Several examples of relevant FPGA utilizations in this context are presented in this paper. Another perspective on FPGA design is to propose a prototyping development system of a fully integrated controller from VLSI technology and SoC design that can include digital control and its analog interface (sensors, ADC, power drivers, etc.) [43]. Interesting and relevant research topics were described along with the social and economic aspects of the field. Most readers would only find a subset of the topics covered relevant for their work, but the purpose was to provide a full picture in order for those readers to be better informed when constructing a threat model and corresponding defense mechanism, as a system is specified and designed [44]. Fuzzy systems accept numeric inputs from the outside world and convert them into linguistic values that can be manipulated by using fuzzy logic operations with linguistic if-then rules given by human operators. The linguistic outputs, the result of the fuzzy logic operation, are converted into numeric outputs which are then delivered to the outside world [18], [21]. In the field of control system, many complex plants are difficult to deal with by the conventional approach because of their nonlinear, time-varying behavior and imprecise measurement information. Nevertheless, human operators can handle these complex plants by their practical experience. They only need imprecise system states and a set of imprecise states and a set of imprecise linguistic if-then rules. The fuzzy system theory based on fuzzy set and fuzzy logic can be used to deal with such complex systems [17], [21]. To understand what a fuzzy set is, first consider what is meant by what we might call a crisp (conventional or classical) set. A crisp set is a collection of any kind where the membership of an object in the set is either one (totally contained in the set) or zero (totally excluded from the set). Fuzzy set differs from the crisp set by allowing partial or gradual membership. The membership of an object in a fuzzy set may be either one or zero or any value between zero and one. According to the previous definitions the crisp set can be considered as a specific type of fuzzy set [15], [16].

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Dr. asri Sulaiman was born in Malaysia; he received his B. Sc. Degree in (Elect & Comp.) from university putra Malaysia, 1994. Master degree from University of Southampton, UK, 1999.

Ph.D from University of Edinburgh, UK, 2007. He is currently a Lecturer at Department of Electrical and Electronics Engineering, UPM. His current research interests include. Evolvable Hardware (EHW) and Digital Signal Processing(DSP)

Eng. Zeyad Assi Obaid was born in Dyala, Iraq. He received his B. Sc. Degree in control and systems engineering from the University of Technology, Baghdad, Iraq, in 2006.

Cisco Certified Network Association (CCNA) from (Cisco Computer center), Doha, Qatar, 2007. From July 2008 currently is Master Student in control and automation engineering department, university putra Malaysia. His current research interests include fuzzy modeling and fuzzy control systems with FPGA design applications. He has many of Professional Affiliations like, Member in IACSIT, Member in IEEE, Member in ACM, Member in IAENG and Member in the Program committee of the IEEE International Conference on Signal and Image Processing Applications (ICSIPA), by the IEEE Signal Processing Society. He has an industrial experiences such as, from February, 2004 to October, 2006, working as: *Network administrator* in Alkawarizmy Computer Services Company, Baghdad, Iraq and From 20/12/2006 to 31/5/2008 working as *control and computer engineer in* Ezdan Real estate Company (international constructions and trading company), Doha, Qatar.

Assoc. Prof. Dr. M. H. Marhaban. was born in Malaysia; he received his B. Sc. Degree in (Electrical and Electronic Engineering) from university of Sanford, UK, 1998. Ph.D. (Electronic Engineering) form University of Surrey, UK, 2003. A-Level, Mara Science College, Kuala Lumpur, 1995.

Malaysia Certificate of Education, Mara Junior Science College, Taiping, Perak, Malaysia, 1993. Lower Certificate of Education, Sekolah Menengah Gua Musang, Kelantan, Malaysia, 1991. He is currently a Lecturer at Department of Electrical and Electronics Engineering, UPM. His current research interests include: Intelligent Control System and Computer Vision.

Dr. Mohd Nizar Hamidon was born in Malaysia; he received his B. Sc. Degree from university of Malay, Malaysia, 1994. Master degree from the university Kebangsaan, Malaysia, 2001.

PhD from the University of Southampton, UK, 2005. He is currently a Lecturer at Department of Electrical and Electronics Engineering, UPM. His current research interests include. Microelectronics (Sensor Technology), MEMS, Wireless System Devices Fabrication and Packaging.