Digital ANFIS Model Design

Prasad R. Pande, Prashant L. Paikrao, Devendra S. Chaudhari

Abstract*— Neuro-Fuzzy systems are hybrid intelligent systems which combine features of both paradigms- fuzzy logic and artificial neural networks. Adaptive Neuro Fuzzy Inference System (ANFIS) is one of such architecture which is widely used as solution for various real world problems. This paper describes development of an ANFIS model for FPGA implementation. Model can be realized with hardware descriptive language thus making it reusable, reconfigurable and independent of applications. This digital ANFIS firmware can be proven to be optimal solution in terms of cost, speed of operation and flexibility in design methodology.

***Keywords*— ANFIS, Digital System, FPGA, HDL, Neuro-Fuzzy System**

I. INTRODUCTION

Since last two decades, fusion of Artificial Neural Networks (ANN) and Fuzzy Inference Systems (FIS) have attracted the growing interest of researchers in various scientific and engineering areas which have been resulted into development of Neuro-Fuzzy Systems (NFS). Due to the growing need of adaptive intelligent systems to solve the real world problems like automotive control, pattern recognition, human-machine interaction, experts system, medical diagnosis, economics, *etc*., NFS draws attention of many researchers which leads to different modelling techniques for either dedicated or generalized problems.

In recent years, implementations of different neuro-fuzzy architectures like Adaptive Neuro-Fuzzy Inference System (ANFIS) have advanced a lot. Different neuro-fuzzy technologies emerged as optimal solutions for researchers in terms of speed of operation, cost, flexibility, usability and their trade-offs. Scientists have been provided with lot of flexibleness and versatility by neuro-fuzzy approaches so as to simulate or design their systems as per their requirements. It is researcher's and designer's responsibility to identify the perfect solution among available ones for their system by considering its feasibility and different trade-offs.

Real world systems demands for ANFIS hardware model rather than software with a tradeoff between versatility and performance. Since training process of ANFIS model cannot be driven with hardware because of memory dependency, it has to be carried out first as off-line in software. To take full advantage of such heterogeneous solution, integration of all parts of ANFIS is desirable so as to accommodate all the components of a typical embedded system on a single chip.

Also the digital version of ANFIS should offer desired speed short time-to-market, re-usability, and availability of Intellectual Property (IP) cores with high flexibility [1].

Hence the intention behind development is to elaborate comprehensive architecture representing ANFIS model which can be widely used for different applications without using application dedicated resources. Furthermore, model is aimed to be designed in a standard extensively used hardware description language so as to be acceptable among designers and developers.

Digital architecture of ANFIS was proposed to realize on Field Programmable Gate Array (FPGA) using any hardware description language like VHDL. Three input single output nonlinear function was chosen for the analysis of zero order ANFIS model. With respect to this function, ANFIS training was carried out in software and parameters set is obtained from it. After getting parameters list from training, digital architecture is modeled and implemented using hardware description language on FPGA. It used fixed point representation in language to reduce model complexity.

This paper reviewed neuro-fuzzy systems, their importance and applicability in the real world concisely and the generalized ANFIS structure with its adaptive properties and its learning algorithms. High level and moderately internal description of digital architecture of ANFIS is then studied and paper concluded with further possible amendments respect to the model.

II. NEURO-FUZZY SYSTEMS

A. Definitions

Since last few decades, artificial neural networks and fuzzy inference systems have been a major focus of many researches. Fuzzy systems have the ability to represent comprehensive linguistic knowledge understandable to human experts and execute reasoning with use of fuzzy rules. Nevertheless, fuzzy systems do not provide a mechanism to automatically obtain and/or tune those rules. On the other hand, neural-networks are adaptive systems that can be trained and tuned from presented set of trials. Once they are trained, neural-networks can take on new inputs by simplifying the acquired knowledge yet extraction and understanding that knowledge is complicated. In other words, fuzzy systems and neural-networks are complementary paradigms [2, 3]. Limitations in both systems have sparked idea behind the creation of neuro-fuzzy systems where the two techniques are combined in a manner that the limitations of the individual techniques have been overcome. Hybrid neuro-fuzzy systems combine fuzzy logic theory and neural networks in a synergetic fashion. A neuro-fuzzy inference system can be defined as a fuzzy inference system that uses a training algorithm encouraged by neural network architectures [4, 5].

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B. *Classification*

A. Abraham has classified neuro-fuzzy systems into three main categories: cooperative, concurrent and integrated neuro-fuzzy models [6]. Brief classification of neuro-fuzzy inference system is described below.

1. *Cooperative Neuro-Fuzzy Systems*

In cooperative type NFS, membership functions and inference rules required for fuzzy operations are identified by learning of specific ANN. After training, ANN job is terminated and fuzzy inference system lift-up further processes of system. Thus, ANN co-operates with FIS to form a cooperative neuro-fuzzy system [6]. Fuzzy Associative Memories is an example of cooperative NFS where membership functions, rule weights, etc. are usually approximated by neural network from the training data. In another example, the rule base is usually determined by a clustering approach (self organizing maps) or fuzzy clustering algorithms. This cooperative system is known as fuzzy rule extraction using self organizing maps [6].

2. *Concurrent Neuro-Fuzzy Systems*

Unlike cooperative system, neural network and fuzzy inference system works simultaneously to find out rule extraction and membership values of neuro-fuzzy system. Neural network is connected in cascade with FIS or vice versa for mutual operation which results in overall efficient NFS. Systems where input variables of the controller cannot be measured directly or where fuzzy outputs not applicable straight to the process can be treated with Concurrent NFS. Concurrent NFS do not optimize inference system but it could be used where high performance is essential [6].

3. *Integrated (Fused) Neuro-Fuzzy Systems*

Integrated NFS applies features of ANN and FIS both, not in structurally separate but a single inseparable architecture. Cooperative and concurrent NFS models use ANN learning algorithms separately with respect to FIS to determine its parameters while integrated/fused NFS is always a specifically constructed architecture of FIS in a form of ANN. Due to its structural uniqueness, integrated NFSs are fully interpretable and learning can be in supervisory style contrasting to cooperative and concurrent models. Another advantage of integrated NFS is that it employs sharing of data structures and knowledge representation across whole [6]. Fuzzy Adaptive Learning Control Network (FALCON), Generalized Approximate Reasoning based Intelligent Control (GARIC), ANFIS, Neuro-Fuzzy Controller (NEFCON), Self Constructing Neural Fuzzy Inference Network (SONFIN), Fuzzy Inference Environment Software with Tuning (FINEST) and Fuzzy Net (FUN) are some fused architectural models developed by different researchers [6].

ANFIS is such a neuro-fuzzy architecture which has been widely accepted since invented. The ANFIS is essentially a hybrid learning system which can be seen as fuzzy inference system that uses neural network theory to derive its parameters through learning algorithm. It has been used yet for different applications like universal approximator, non-linear system realization, pattern recognition, *etc*.

II. GENERLIZED ANFIS

ANFIS is the fuzzy-logic based paradigm that grasps the learning abilities of ANN to enhance the intelligent system's performance using knowledge gained after learning. Using a given input-output data set, ANFIS constructs a fuzzy inference system whose membership function parameters are tuned or adjusted using hybrid type of neural algorithms. The generalized ANFIS architecture proposed by Jang is summarized below [7, 8].

Let us assume the inference system employs Sugeno fuzzy model, a common rule set with two fuzzy IF – THEN rules. The nonlinear function under system design consideration also used zero order Sugeno model in structure for calculation simplicity. The basic ANFIS architecture is as shown in figure 1, where nodes of the same layer have similar function, as described next.

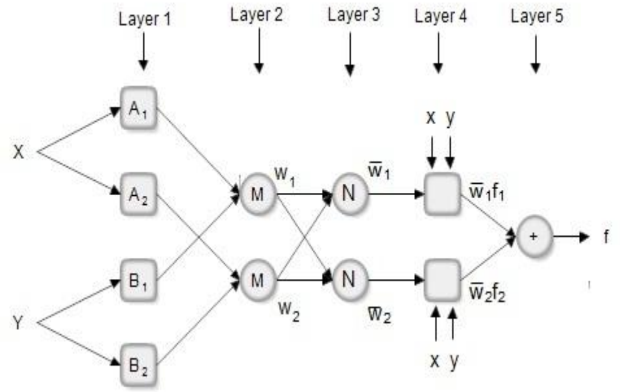

Fig. 1 – Generalized ANFIS Architecture (Source: J.S.R. Jang)

In first layer, input values of universe are converted to their respective membership values by corresponding membership functions as in equations (1) and (2). Here the membership function can be any appropriate parameterized membership function such as generalized bell function like in equation (3); where {*a*, *b*, *c*} is the parameter set referred as Premise Parameters.

LAYER 1: $O_{1,i} = \mu_{A_i}(x),$ for i = 1, 2, or (1)

$O_{1,i} = \mu_{B_{i-2}}(y),$ for i = 3, 4 (2)

$$\mu(x) = \frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \quad (3)$$

In layer 2, obtained membership values are multiplied in order to obtain firing weight or strength of the fuzzy rules given in equation (4). Hence outputs of nodes are product results of all inputs.

LAYER 2: $O_{2,i} = w_i = \mu_{A_i}(x) \times \mu_{B_i}(y)$ for i = 1, 2 (4)

Third layer deals with normalization of firing strength of rules. This calculates the ratio of the i^{th} rule's firing strength to the sum of all rules firing strengths in equation (5).

LAYER 3: $O_{3,i} = \bar{w_i} = \frac{w_i}{w_1+w_2},$ for i = 1, 2 (5)

In fourth layer, the values from the third layer are multiplied with equivalent Consequent Parameter set {d_i, e_i, g_i }

LAYER 4: $O_{4,i} = \bar{w_i} f_i = \bar{w_i}(d_i x + e_i y + g_i)$ (6)

At last, fifth layer computes the overall output as the summation of all incoming signals.

LAYER 5: $O_{5,i} = \sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i}$ (7)

The learning algorithm for ANFIS is a hybrid algorithm that is a combination of gradient descent and least squares methods. In the forward pass of the hybrid learning algorithm, node outputs go forward until Layer 4 and the consequent parameters are determined by the least-squares. In the backward pass, the error signals propagate backward and the premise parameters are updated using gradient descendent. The hybrid learning approach converges much faster by reducing search space dimensions of the original back propagation method [7, 8].

ANFIS model is not a structurally rigid adaptive network. Layer 3 and 4 can be merged together and overall ANFIS could result into four layer structure. In that case, weight normalization is performed at very last stage [8]. This theory has been into consideration while designing the digital ANFIS system.

IV. DIGITAL ANFIS DESIGN

Digital hardware architecture of ANFIS which can be implementable on FPGA was first proposed and developed by H.J.B. Saldana and C.S Cardenas for two input nonlinear function [9]. Further, advancement has been done for three input single output nonlinear function by them [10]. The system was described in HDL and implemented on FPGA. It used fixed-point two's complement representation for inputs, parameters, outputs and was parametarizable.

The training process for selected function is carried out off-line in MATLAB environment. Either triangular or trapezoidal membership functions are used in the premise of the fuzzy rules. All these parameters along with consequent parameters are fixed during further system operation and stored in memories of respective sub-blocks of digital system. Instead of using dedicated resources from the FPGA, a sequential multiplier and a divider are designed according to the multiplication and division algorithms respectively.

The digital architectural design of ANFIS is divided into four subsystems – Fuzzifier, Permutator, Inference and Defuzzifier as shown in figure 2. Brief narration about each subsystem is given below.

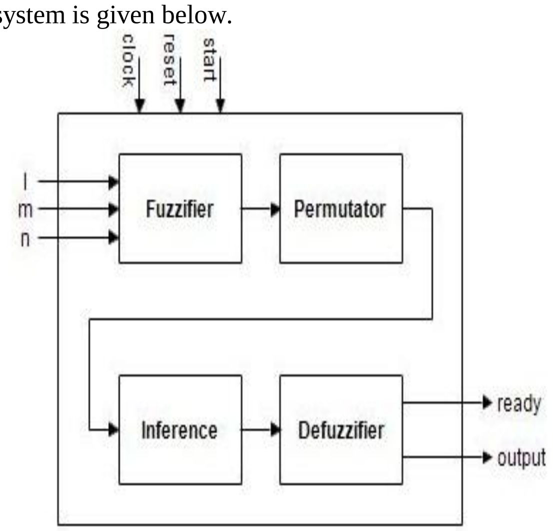

Fig. 2 – Digital ANFIS Architecture

In this, *l*, *m*, and *n* are numeric inputs to the system. Along with it, *clock* is master clock required for system operation; *reset* is asynchronous reset provided and *start* is system initiation signal provided to the system. The *output* is the overall system output and *ready* signal indicate end of system operation.

A. *Fuzzifier*

The first subsystem calculates the membership values for each of the three inputs *l*, *m* and *n*. As shown in figure 3, it has total three -

- Initial storage registers (store_l, store_m, store_n) one for each input.
- Read-only-memories (param_l, param_m, param_n) used to store the parameters of the triangular membership functions.
- Membership function blocks (fun_l, fun_m, fun_n) that evaluate the membership value of their respective input.

It also comprised a controller to manage all the operations flow. All inputs are stored in respective registers after *start* signal given to Fuzzifier. With every membership value computation, *f_ready* signal is generated to indicate Permutator that a value is available for storage.

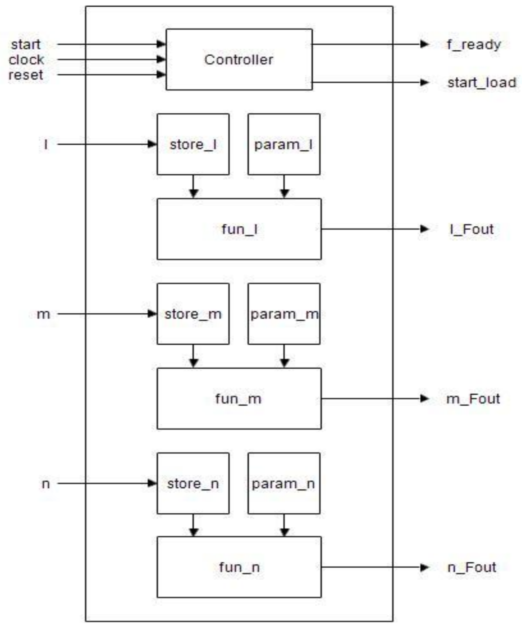

Fig. 3 - Fuzzifier subsystem

B. *Permutator*

The Permutator stores the membership values that are calculated by the previous subsystem. Each possible permutation of these values are generated so that all membership values can be multiplied by the next subsystem.

Permutator comprised of three circular shift registers- Circ_fun_l, Circ_fun_m and Circ_fun_n, where the storage and permutation process is carried out, and a controller as shown in figure 4. For faster operation of the system, membership function whose value is zero is discarded and no further multiplication process carried out for the same.

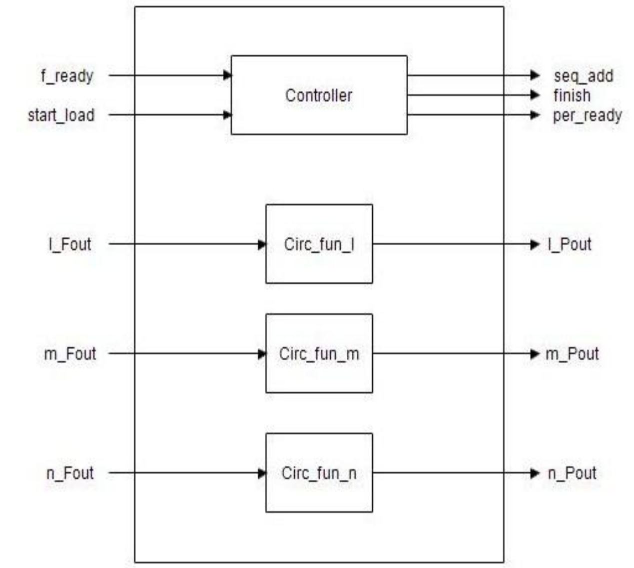

Fig. 4 - Permutator subsystem

C. Inference

The numerator (*Num*) and the denominator (*Den*) of equation (7) are calculated separately by Inference subsystem. It has three stages and a controller shown in figure 5.

- Stage 1 contains one register (R_seq) and one multiplier (Multiplier 1). In this stage, membership values are multiplied to obtain the weight of the rule.
- Stage 2 contains one multiplier (Multiplier 2), one register (R_sum_wght) and one ROM (seq_ROM). In the second stage, weight of the rule is multiplied by the corresponding consequence parameter. At the same time, the weight is stored in a register.
- Stage 3 comprises two accumulators (Num_Acc, Den_ Acc) for storage.

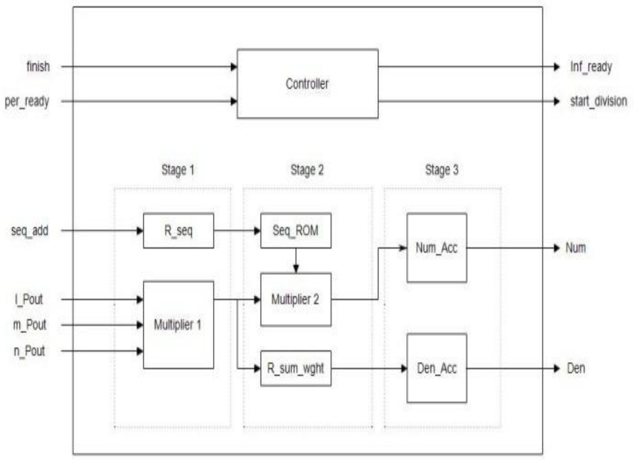

Fig. 5 - Inference subsystem

D. Defuzzifier

The Defuzzifier subsystem carry out the division operation between signals *Num* and *Den* obtained from Inference subsystem. The result of this division signifies to the output of the ANFIS. It contains a divider, and a controller as shown in figure 6. Its function is described by the following equation:

$$output = \frac{Num}{Den} = \frac{\sum_i f_i w_i}{\sum_i w_i} \quad (8)$$

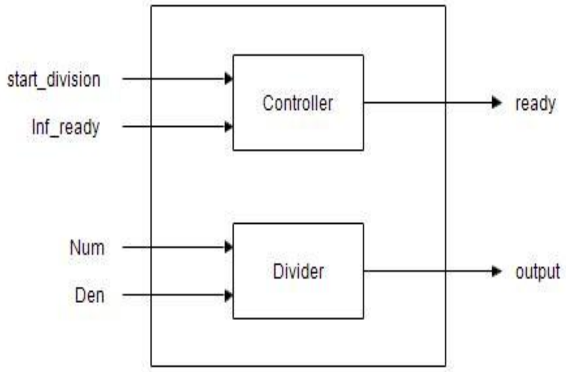

Fig. 6 - Defuzzifier subsystem

Post-place and route simulations are carried out on XILINX ISE environment. 8 bit and 16 bit fixed point precision was used for all signals including parameters which are stored previously in ROMs derived from MATLAB training. Random values were presented to the system and their results are verified with results obtained from function itself. Furthermore, relative error and time response were evaluated for FPGA outcomes and MATLAB results for comparison in order to measure correctness and performance of the system.

V. CONCLUSION

A digital architecture of ANFIS and its VHDL realization for three input nonlinear function generation is discussed in this paper. Initially, a review of neuro-fuzzy systems has been considered with their classification and need to face real world challenges. Further, a generalized ANFIS structure is studied with necessary equations for designing digital architecture for FPGAs. The digital model is definitely characterize a heterogeneous firmware of one of famous neuro-fuzzy model for handling nonlinear system, where hardware realization of model identifies, learns and behaves with nonlinearity and training could be carried out using software.

Presented digital architectural design of ANFIS is restricted with single membership function – either triangular or trapezoidal. System complexity increases with membership functions like generalized bell *etc*. though real world demands it. Once system configured for single membership value, it needs hardware changes in order to shift from one membership function to another if unsatisfactory results obtained. Hence system could be redesigned for being dynamic for any membership function and with reduce design specific to fuzzification calculations for faster operation.

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Prasad R. Pande received his Bachelors degree in electronics and telecommunication engineering from Sant Gagde Baba Amravati University, Amravati in 2008. He has corporate experience of nearly two and half years as System Engineer in IBM India Pvt. Ltd. He also worked as assistant professor in P. R. Patil College of Engineering, Amravati. Currently he is pursuing his

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He has worked as Chairman / Member on different university and college level committees like Examination, Academic, Senate, Board of Studies, etc. he chaired one of the Technical sessions of International Conference held at Nagpur. He is fellow of IE, IETE and life member of ISTE, BMESI and member of IEEE (2007). He is recipient of Best Engineering College Teacher Award of ISTE, New Delhi, Gold Medal Award of IETE, New Delhi, Engineering Achievement Award of IE (I), Nashik. He has organized various Continuing Education Programmes and delivered Expert Lectures on research at different places. He has also worked as ISTE Visiting Professor and visiting faculty member at Asian Institute of Technology, Bangkok, Thailand. His present research and teaching interests are in the field of Biomedical Engineering, Digital Signal Processing and Analogue Integrated Circuits.