ISSN 2278-3091
Volume 8, No.1.2, 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse2181.22019.pdf
https://doi.org/10.30534/ijatcse/2019/2181.22019

Design of an FPGA-based Intelligent Gateway for Industrial IoT

Tuncay Ercan[1], Ahmed Khazal Al Azzawi [2]
[1] Engineering Faculty, Computer Engineering Department, Yaşar University, İzmir, Türkiye, tuncay.ercan@yasar.edu.tr
[2] Engineering Faculty, Computer Engineering Department, Yaşar University, İzmir, Türkiye, ahmedkhazal@gmail.com

ABSTRACT

The use of information technologies in the implementation of industry 4.0 applications has naturally attracted the attention of many entrepreneurs and the business community. Industry 4.0 applications enabled cost reduction and efficiency in Industrial production systems. However, there are difficulties in the process of reliable data collection, integration and analysis of production-related data. The authors propose FPGA-based hardware and ANFIS software-driven intelligent algorithms to use temperature and humidity sensor test data for these processes. This approach achieves a significant performance and resource utilization rate in Industrial IoT systems and shows 55% decrease in the amount of HW resources in FPGA.

Key words: ANFIS, FPGA, Industry 4.0, IoT.

1. INTRODUCTION

In the industrial and economic sectors, efficiency and cost reduction in production, which has become more important with the theme of industry 4.0. The use of information technologies in the implementation of industry 4.0 applications has naturally attracted the attention of many entrepreneurs and the business community [1]. All industrial institutions have difficulties in the process of reliable collection, integration and analysis of production-related data. Due to the rapid development of the process from the beginning of the data collection to providing information to Decision Support Systems (DSS), different hardware, software and network systems are being used to optimize these services effectively. Naturally, this situation leads to the complexity of the Machine Learning (ML) supported algorithms used and taking a long time to process. ML gained a lot of importance on almost every area due to its ability to improve analysis process on a given data set. There is a need of framework that can effectively track and monitor the system components and the overall contextual information in the industrial environment with an application view. Over the last few years, many of the Internet of Things' (IoT) solutions have been heavily involved in the industrial market [2]. Perera et al have examined some new and innovative IoT systems to increase data richness in the industrial environment. They have surveyed a lot of smart IoT solutions, technologies and applications and discussed them in five different categories such as smart wearable, smart home, smart city, smart environment and smart enterprise [3]. It is very important to evaluate the data collected from environmental sensors (temperature, humidity, wind, odor, etc.), industrial production devices and analyze them for unpredicted problems. Many R&D studies in academic research institutes, private and public organizations are currently focusing on new systems that are needed in those aforementioned categories. FPGAs (Field Programmable Gate Array) have started to take its place in new applications with their high performance features for parallel computing and signal processing. The biggest advantage of using the FPGA device as a new component in the industrial environment is that the different hardware features of FPGA (flexible and reusable integrated circuit, computing parallel tasks, cost efficiency, multiple input/output capability etc.) that can be designed by a developer for different application platforms after production. In addition, FPGA allows many tests for faster prototyping to be repeated many times and corrected [4], [5]. Nearly any ML application including data extraction, filtering, and classification and prediction algorithms can exploit the advantages of the reconfigurable nature of FPGA.In this study, we propose an FPGA-based hardware and software-driven intelligent algorithms for these processes, which are generally controlled by PLC and computer-aided systems. This approach places FPGA component as a smart gateway for wireless sensor nodes in the industrial environment and achieves a significant performance and resource utilization rate in Industrial IoT systems. We aimed to investigate the problems such as data cleaning, data integration and data transfer which may occur when the data of different sensors and industrial systems are brought together under an automation system and analyze them by ML algorithms to be developed on FPGA. The rest of this paper is organized as follow. Section II presents the main Industrial IoT trends and our research approach for a smart gateway problem. Section III explains the proposed system architecture. Section IV presents ML algorithms and the design issues used in FPGA. Section V defines a GUI for real-time control management designed in Matlab. Section VI concludes the paper and discusses future directions.

2. INDUSTRIAL IOT TRENDS AND RESEARCH APPROACH

2.1 Industrial Automation Architecture

Today's industrial automation architectures in different factories are mainly distributed rather than vendor dependent central structures. Distributed structures enable the use of automation devices with different Industrial communication protocols such as Profibus, Foundation Fieldbus, Interbus, and Canbus etc. The use of different protocols on the same network leads to unpredicted communication delays that cause disruptions in the production chain. Cost reduction in overall production and increasing efficiency have recently become one of the most critical issues for all industrial organizations to acquire a competitive advantage. It is extremely important to collect required data from the sensors of production devices and analyze them for significant and critical problems in the future. While microprocessor based gateway devices fail to solve this problem for different protocols to work together, but FPGA-based smart gateways perform extremely well due to their resource-rich features. As an example, IFDAQ (Intelligent FPGA Data Acquisition), an FPGA-based information collection system developed for CERN, can combine information from 256 different serial channels at 3.5 GB/s with a new protocol called UCF (Unified Communication Protocol) to convert it to IP protocol [6]. Today's technology requires the storage of collected information in high-capacity storage systems provided by cloud systems. For this reason, it is imperative that classical industrial protocols must be collected on a gateway and translated into a "High-speed Ethernet Protocol (HSE)". FPGA-based gateway designs that can meet industrial communication needs attract the attention of researchers. The HEIS "HART-Ethernet Intelligent Subsystem," developed to convert the legacy HART protocol used in process control systems to Ethernet protocol, removes the need for a large number of modem and protocol converter chains, enabling the connection of standard IP switching devices by increasing the rate of information transfer [7]. In the literature, there are different studies aiming at the development of Profibus-4G gateways developed for data transmission from remote locations without Modbus-Ethernet and cable infrastructure [8], [9].

2.2 FPGA as an Intelligent Gateway

After investigating about what can be done by using FPGA as an intelligent gateway in the environment of Industrial Internet of Things (IIoT), the tasks that need to be implemented should be determined as follows:

- Aggregating data from different numbers of (industrial) sensors,
- Designing an FPGA-based intelligent gateway,
- Developing an intelligent control unit to manage sensors and other industrial sub-components,
- Developing machine learning algorithms (ANFIS) for aggregated data for predefined and variable functions,
- Analyze industrial and environmental sensor data together to provide a smart reaction for decision support systems,
- Building a single management system to monitor and manage data traffic by different time, location, functions and the increasing number of devices.

3. SYSTEM ARCHITECTURE

Sensors such as heat, humidity, and gas which will collect environmental information plus special sensor devices to perceive the hardware and mechanical differences in manufacturing devices will be collected from their own layers (FPGA 1, FPGA 2). Together with the production and operating data on ERP database, all the devices in the industrial environment are connected to the intelligent control box (FPGA 3). Thus, the information about the environmental sensors and production devices, which are separated and classified, will be combined with Business ERP information on the IP Switch and forwarded to FPGA 3 for a new analysis and decision support. Figure 1 below shows this architecture.

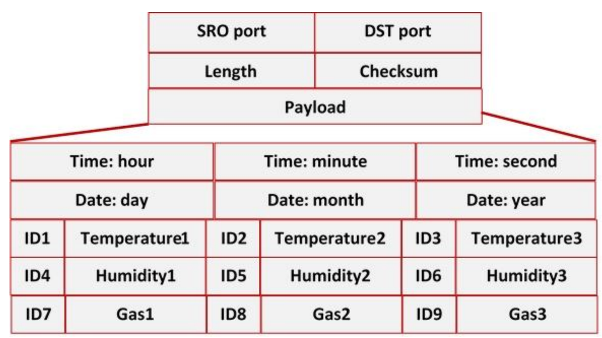

Figure 1: Layered Proposed FPGA-based Smart Control

Different ML algorithms will be used as system software in FPGA based gateways and intelligent control box for the complete analysis and Decision Support [10]. After the data entry process from the real-time test environment is completed, analysis, classification and efficiency processes will be performed in accordance with the predetermined parameters for the sensor and industrial device data.

Our prototype system has been established to evaluate the environmental sensor information and mainly comprises these 3 units;

1. **Aggregation Unit**: Based on Arduino microcontrollers that collect the data from different sensors,
2. **Multi-function Unit**: Xilinx FPGA device as the main controller unit,
3. **Communication Unit**: Connects both FPGA devices and ERP database with Monitor PC.

In the Aggregation Unit, there are three different sets of sensors (3-temperature sensors, 3-humidity sensors, and

3-gas sensors) connected to the Arduino microcontroller. Arduino will collect the data from these sensors and associates each data with a unique 8-bit ID. Arduino can be programmed to organize different sensor data as given in Figure 2.

Multi-function Unit (only FPGA 2 in our case) receives the collected data from the Aggregation Unit and performs multiple functions like classification, prediction and decision-making. It initializes the hardware platform, control and performs all the following functions based on ANFIS algorithm; (1) Decision making (light adjuster, air conditional adjustment, and alert), (2) Classification according to types (temperature, humidity, and gas sensors), values (low, moderate, high, very high, and extreme), and locations (inside or outside the home). Figure 3 demonstrates all functions that are computed by the FPGA processing system.

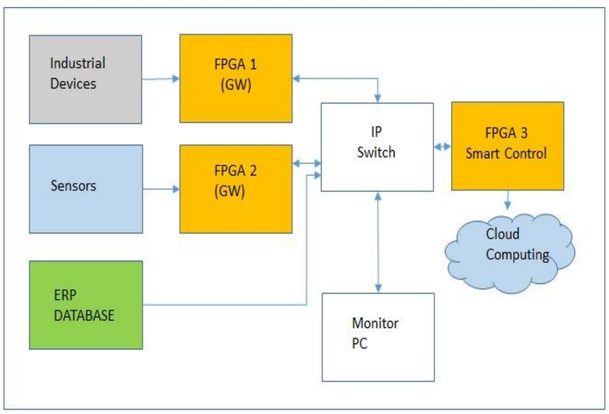

Figure 2: Pre-defined message formats to be organized in FPGA

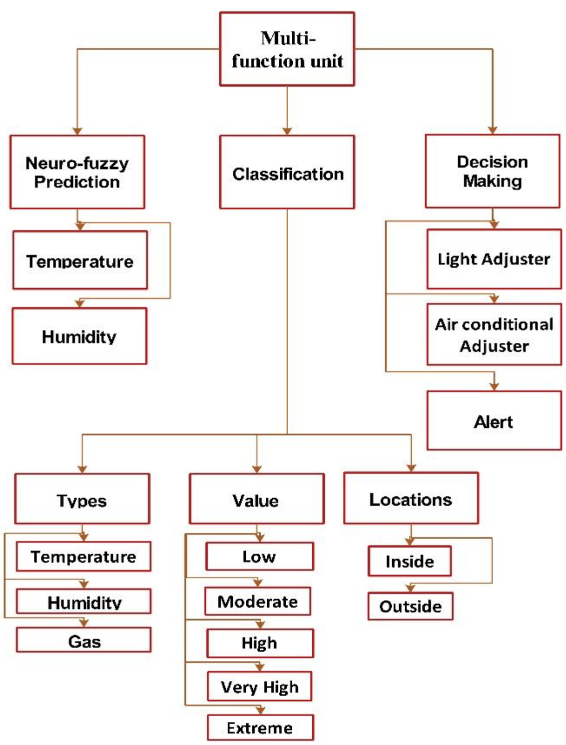

Figure 3: Functions Computed in FPGA

4. INTELLIGENT ALGORITHMS AND HW DESIGN

After combining the data collected from the sensors and the industrial devices including the status and location changes, the common features and recurrences that occur depending on time can be determined by ML algorithms [11]. Different algorithms like Decision Tree, Artificial Neural Networks, Bayesian Networks, Support Vector Machine, K-Nearest Neighbor and Kohonen Networks can also be evaluated according to the best result. Later, the results can be evaluated by TensorFlow software to acquire more precise values [12].

Industrial environments where the proposed architecture setup, may contain different production devices such as molds, presses, packaging units, different CNC machine tools. The artificial intelligence algorithms use the data set extracted and formed from the different sensors connected to these industrial devices. The additional parameters recorded on the ERP database (sound, acceleration, temperature, pressure, former maintenance information etc.) and new deep learning algorithms can be combined to predict the pre-defined problems [13]. We used Adaptive-Neuro-Fuzzy Inference System ANFIS which is an example of Hybrid Neuro-Fuzzy systems. ANFIS is one of the most successful algorithms that integrates the advantages of both Neural Networks (NN) and Fuzzy Logic into a single prototype [14]. The features of an ANFIS involve: (1) easy to implement, (2) fast and accurate learning, (3) strong generalization abilities, (4) excellent explanation facilities through fuzzy rules, (5) easy to incorporate both linguistic and numeric knowledge for problem solving [15]. ANFIS algorithm has been performed on FPGAs. We used a Xilinx Zynq xc7z020 evaluation board as a hardware platform. In order to actualize our application adequately, the project is separated into steps: The first step in our hardware design is based on Vivado High-Level Synthesis (HLS) to create an IP core for our modifying ANFIS algorithm. We use C language using 32-floating point technique, then we export our IP core to the Xilinx Vivado Suite in order to connect to the other hardware elements in FPGA evaluation board. Figure 4 shows the amount of hardware resources that required designing the single ANFIS core.

Utilization Estimates

Summary

Name	BRAM_18K	DSP48E	FF	LUT
DSP	-	-	-	-
Expression	-	-	-	-
FIFO	-	-	-	-
Instance	0	24	5847	10000
Memory	-	-	-	-
Multiplexer	-	-	-	-
Register	-	-	-	-
Total	0	24	5847	10000
Available	280	220	106400	53200
Utilization (%)	0	10	5	18

Figure 4: Amount of FPGA Resources for ANFIS Algorithms

Using the optimization directives such (data flow, loop merge, and pipeline) within the core is one of the reasons for reducing amount of hardware resources consumption. The next step is to use Xilinx Vivado Suite to build the overall hardware design based on xc7z020 kit. Figure 5 shows the overall hardware design.

This hardware design consists of four main parts:

- Arduino microcontroller interface to obtain the data from temperature, humidity sensors. Then, it sends the collected data to FPGA through Ethernet communication.
- Configurable Block RAM (BRAM) stores the different sensing data in different banks.
- ARM Cortex-A9 MP dual core SYNQ processing system which initializes the hardware platform, ANFIS cores, and process the data.
- Four ANFIS IP cores that hold our modifying algorithms in order to predict the weather conditions for temperature and humidity.

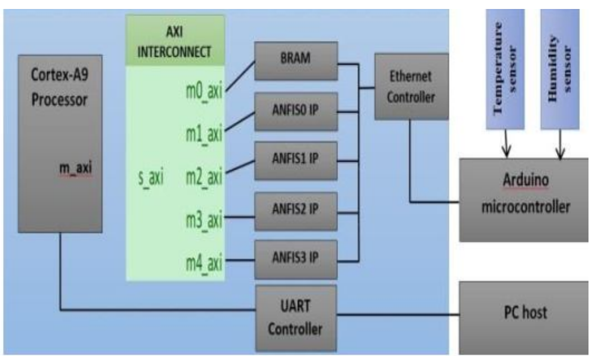

Figure 5: Hardware Design

The implementation process of the hardware design shows that we use 51% of slice LUTs, 22% Flip Flops, less than 6% BRAM, 3% Global Buffers (BUFG) ,44% DSP block and other resources which explained in Figure 6.

Figure 6: Utilization Design Values

5. GUI FOR MANAGEMENT CONSOLE

A simple Graphical user Interface for real-time control management can be designed in Matlab [16]. This interface is based on Client/server architecture and reached over the Web. This infrastructure consists of client software, server software and database. The client software is a web interface that users can control by any mobile device with internet access. With the user interface, an abnormal condition from sensors and/or industrial systems will be detected immediately. Collected data will be classified according to the pre-defined parameters, analyzed and reacted quickly for abnormal or requested situations. Figure 7 shows a prototype GUI prepared in Matlab. It can display all sensors and industrial devices one by one and control them interactively. This console has five parts denoted by the red numbered circles: (1) sensor types and IDs, (2) real-time data from sensors and prediction data, (3) classification data, (4) real time clock, (5) system display for predicted problems.

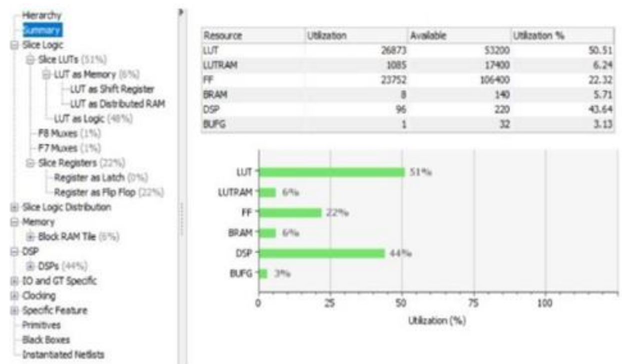

Figure 7: Matlab Graphic User Interface (GUI)

6. CONCLUSION AND FUTURE WORK

In this paper, we propose a new modification of ANFIS algorithm and implement it as software and hardware components. The new modification speeds up the execution time and reduces the amount of hardware resources by adding a new hidden layer to minimize the number of parameters in the output layer. We also successfully built and implemented the ANFIS in a reconfigurable Zynq xc7z020 FPGA board. This hardware permits multiple ANFIS algorithms to work in parallel and deals with different types of data sets. Arduino microcontroller and FPGA as the hardware components of the proposed system play a key role to reduce the execution time and power consumption since they separate the tasks between different sensor groups. The results show that our proposed modification, gave us amazing results in training phase compared with a standard ANFIS architecture. Better results in the testing phase, in addition to minimizing the amount of hardware resources were obtained. Our GUI helps monitoring and managing existing IIoT data. Collecting data through such IoT solutions and analyzing them at a large scale will offer significant value for the increased productivity and cost effectiveness. Since the existing technologies and regulations are not sufficient to support such a detailed data management lifecycle, sensors embedded IoT solutions in the industrial environment could gain consumers' confidence by the help of using FPGA-based smart gateways in every step of data management. Future research efforts will focus on developing novel efficient and scalable algorithms to adapt to uncertain data sizes and variety such as data warehouse, batch processing systems, and stream processing systems of different industrial systems or even in a complete supply chain.

ACKNOWLEDGEMENT

This work was supported within the scope of the scientific research project which was accepted by the Project Evaluation Commission of Yasar University under the project number and title of BAP054_Design of an FPGA-based Control Unit for WSNs.

REFERENCES

1. T. Ercan, M. Kutay, **Endüstride Nesnelerin Interneti (IoT) Uygulamaları**, Afyon Kocatepe University, Journal of Science and Engineering, 16(3), pp. 599-607, December 2016.
   https://doi.org/10.5578/fmbd.43411
2. P. Charith et al., **A Survey on Internet of Things From Industrial Market Perspective**, IEEE Access, Vol.2, pp.1660-1679, 2014.
   https://doi.org/10.1109/ACCESS.2015.2389854
3. Saravanan S., Hailu M., Gouse G.M., Lavanya M., Vijaysai R. (2019), **Optimized Secure Scan Flip Flop to Thwart Side Channel Attack in Crypto-Chip,** In: Zimale F., Enku Nigussie T., Fanta S. (eds) Advances of Science and Technology. ICAST 2018. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 274. Springer, Cham
   https://doi.org/10.1007/978-3-030-15357-1_34
4. C. Perera et al., **The Emerging Internet of Things Marketplace from an Industrial Perspective: A Survey**, IEEE Transactions on Emerging Topics in Computing, Vol.3, No.4, pp.585-598, 2015.
   https://doi.org/10.1109/TETC.2015.2390034
5. S. Trimberger, **Field-Programmable Gate Array Technology**, Norwell, MA, USA:Kluwer, 1994.
   https://doi.org/10.1007/978-1-4615-2742-8
6. S. Trimberger, **Three ages of FPGAs," Highlights of the International Symposium on Field-Programmable Gate Arrays**, ACM, pp.1-18, 2011.
7. Bai et al., **Intelligent FPGA Data Acquisition Framework**, IEEE Transactions on Nuclear Science, Vol.64, No.10, pp.2761-2764, 2017.
   https://doi.org/10.1109/TNS.2017.2743101
8. P. Papazian and M. Babaita, **FPGA Implementation of a HART-Ethernet Smart Industrial Interface**, Proceedings of IEEE 38th International Conference on Telecommunications and Signal Processing, pp.1-4, 2015.
   https://doi.org/10.1109/TSP.2015.7296457
9. Dr.G. Mohammed Gouse, Chiai Mohammed Haji, Dr. Saravanan, **Improved Reconfigurable based Lightweight Crypto Algorithms for IoT based Applications**, Journal of Advanced Research in Dynamical & Control Systems, Volume 10 Issue 12 Pages 186-193
10. Chhatrawala et al., **FPGA Based Data Acquisition with Modbus Protocol**, Proceedings of 3rd IEEE International Conference on Computer and Communications, pp.1251-1254, 2017.
11. Zhou et al., **Design of the Embedded Gateway for 4G and PROFIBUS-DP Based on FPGA**, Proceedings of 3rd IEEE International Conference on Computer and Communications, pp. 748-752, 2017.
    https://doi.org/10.1109/CompComm.2017.8322643
12. T. Safoian, **AI and IoT Lead the Way For Enterprise New Tech Investment in 2018**, May 29,Forbes, https://www.forbes.com/sites/forbestechcouncil/2018/05/29/ai-and-iot-lead-the-way-for-enterprise-new-tech-investment-in-2018/#74fcfa975046, Last Access: 18 September 2018.
13. E. Alpaydın, **Introduction to Machine Learning**, ISBN 978-0-262-01243-0, MIT Press, 2010.
14. **TensorFlow**, https://www.tensorflow.org/, Last Access: 18 September 2018.
15. A. Gomperts et al., **Development and Implementation of Parameterized FPGA-Based General Purpose Neural Networks for Online Applications**, IEEE Transactions on Indus-trial Informatics, Vol.1, No.7, 2011.
    https://doi.org/10.1109/TII.2010.2085006
16. A. Khazal, T. Ercan, **ANFIS Analysis of Wireless Sensor Data with FPGA**, ACTA INFOLOGICA, 2(1), pp. 22-32, 2018.
17. Janusz, K. (2002), **Neuro-fuzzy architectures and hybrid learning**, Springer-Verlag,ISBN 978-3-7903-1802-4, Berlin/Heildelberg.
18. M. Delen, Matlab GUI, http://muratdelen.com/matlab-grafik-arayuzu-matlab-gui, Last Access: 17 September 2018.
19. Dr.S. Jayachitra Dr. Mohammed Gouse Galety, **A Smart Management System for Electric Vehicle Recharge Using Hybrid Renewable Energy**, Journal of Advanced Research in Dynamical and Control Systems (ISSN: 1943-023X), Volume 11 Issue 1 Pages 146-153.
20. N.Saritha Devi, K.S.R.Raju, A.Madhu and R.Raja Sekhar, **Safety and Security for School children's Vehicles using GPS and IoT Technology**, International Journal of Advanced Trends in Computer Science and Engineering, Volume 7 No. 6 (2018), 82 – 86