Integration of a Wireless Sensor-actuator Network and an FPGA for Intelligent Inhabited Environments

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Abstract: Wireless Sensor and Actuator Networks together with processing elements named *intelligent agents* are achieving great importance in environmental control. The trend in this field points to implement small, low power, low cost and fast systems, which is in general, hard to achieve. In this paper, an electronic system that consists of several sensors and actuators and a FPGA endowed with Neurofuzzy based intelligent algorithms is presented. The purpose of this work is to demonstrate the effectiveness of the FPGA to provide intelligence to a Wireless Sensor and Actuator Networks. As example of application, a system which acts over a floor lamp intensity and an opening of a window in an autonomous way is presented. This autonomous action is calculated by the FPGA based on several parameters provided by the network (temperature, humidity and luminosity). By integrating the low power WSAN and the FPGA-based Intelligent Agent, a small, low power, low cost high-performance intelligent environment system is achieved.

1 INTRODUCCTION

In the last decade, the research area known as *Wireless Sensor and Actuator Networks (WSAN)* has rapidly grown mainly due to several technological advances such as the hardware miniaturization, the maturity of the wireless technologies and protocols, and also the sensor integration. The area is at present quite mature for small networks and hence, the number of application fields where WSAN can be found is very large (Dargie, 2010): Environmental Control (Ambient Intelligence, Home Automation, Intelligent Environments) (Cook, 2009), Body Area Networks (health care, telemedicine, elder care, remote patient monitoring) (Acampora, 2014), Machine-to-Machine Communications, Internet of Things (IoT), surveillance, manufacturing, etc.

Together with the sensor network, a processing counterpart to handle the amount of information gathered by the sensors is often required. In many of cases, these processing elements must provide, in autonomous scenarios, a response which is sent back to the actuators in the network. In addition, many applications demand those elements to be small, low power, low cost but fast enough to provide real-time response, which is in general hard to achieve: i.e., intelligence demands high computational power and therefore large size elements with high power consumption.

In order to face those requirements, in Inhabited Intelligent Environments (also called Ambient Intelligence Environments), where a number of sensors and intelligent elements have to be deployed throughout the environment without the user being aware of its presence, *Intelligent Agents* are proposed (Jang, 1997). Intelligent Agents are autonomous units of intelligence whose actions are driven by a goal; they are able to take decisions based on their internal state and information collected from the environment. In this sense, soft computing approaches (Doctor, 2005), mainly fuzzy systems and neural networks are commonly used.

In this paper we propose an electronic system to control ambient parameters in an intelligent inhabited environment. The system is based on a WSAN, which receives/sends data from/to the environment and on a FPGA which addresses the Intelligent Agent. The Intelligent Agent implemented on the FPGA is, in turn, based on several Neurofuzzy systems whose ability to learn and model the dynamics of smart environments has been demonstrated by the authors in recent works (Del Campo, 2012).

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As will be explained throughout this article, the proposed system meets the requirements above mentioned related to the trade-off between high performance on the one hand and low power, low cost and small size on the other. In addition, it has some other important advantages like flexibility and scalability.

To well illustrate the proposed system, a particular implementation has been carried out. This implementation addresses the control of the intensity of a floor lamp and the opening of a window in an intelligent environment, taking into account the values of temperature, humidity and luminosity inside the room and also the value of outside temperature.

The rest of the article is organised as follows: Section 2 describes the Neurofuzzy algorithms that are used in the system as Intelligent Agents. Section 3 presents the global architecture of the proposed system. In Section 4 an implementation example is presented. We explain all the particular details related to the hardware and software subsystems. Finally, Section 5 presents the main conclusions of the work.

2 NEURO-FUZZY SYSTEMS FOR MODELLING INHABITED ENVIRONMENTS

NeuroFuzzy Systems (NFS) are intelligent algorithms that combine the learning capabilities of Neural Networks and the interpretability of the knowledge of Fuzzy Systems. NFS have been used in different fields because of their modelling abilities when dealing with real-live scenarios. In particular, the authors have proved (Del Campo, 2012) how NFS can act as suitable Intelligent Agents to control ambient parameters in inhabited environments. In particular, the authors proposed a PWM-ANFIS system which is a low computational-cost version of the well known ANFIS system (Jang, 1993).

Basically, ANFIS is a Fuzzy Inference System that can be represented as a Neural Network and hence, it can be endowed with typical Neural Networks training algorithms. By applying some particular restrictions on the membership functions, a computationally-efficient algorithm is obtained with little loss of modelling performance as was shown by the authors in works (Echanobe, 2008). These restrictions are: i) the membership functions are overlapped by pairs, ii) they are triangular shaped, and iii) they are normalized in each input dimension. As a result of this, the output of the system has piece-wise multilinear (PWM) behaviour and hence the authors have referred to it as PWM-ANFIS.

The PWM-ANFIS system is able to learn from a set of sample data, and, once it has learned, given other real data, it will respond according to the learning. In order to provide real-time response of PWM-ANFIS algorithms, the authors proposed in previous works an FPGA-based efficient hardware architecture (Echanobe, 2008). This implementation was carried out taking into account the great amount of parallel resources available in FPGAs. This PWM-ANFIS efficient hardware architecture is used in this work.

3 SYSTEM ARCHITECTURE

The proposed complete system is based on the architecture depicted in figure 1. It comprises two main parts: The Wireless Network and the FPGA-based Intelligent Agent. Using the sensors included in the Wireless Network, several environmental data are measured. Those measurements are sent by the WiFi module to the FPGA, where the signals to drive the actuators (also presented in the Wireless Network) are calculated. This calculus is performed by a PWM-ANFIS algorithm, which has been previously trained to simulate a user behaviour facing those conditions. So, the complete system will act as the user would do it.

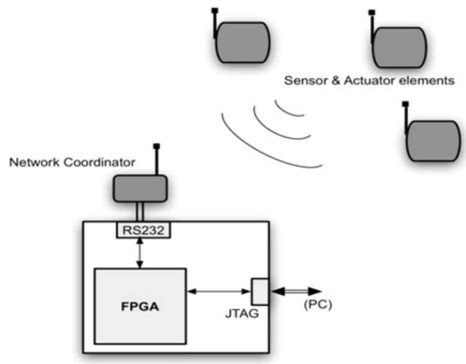

Figure 1: Architecture of the proposed system.

In the following paragraphs we analyze the architecture in detail.

3.1 WaspMote: A Sensor and Actuator Wireless Network

The wireless network is based on the *Waspmote Platform* (Libelium Comunicaciones Distribuídas, 2013). This is a modular and flexible hardware platform to easily implement and deploy a WSAN. The main element of this platform is the *Waspmote* board which is based on the ATmega 1281 microcontroller. The board contains several connectors or expansion ports that permits to attach (in an stacked way) a sensor board which integrates sensors or actuators and a WiFi communication module (called XBee) to handle the wireless communication. Figure 2 shows these three elements assembled. We will refer to this 3-part body as Waspmote-Sensor module. Up to eight different wireless protocols are supported by the WiFi module: 802.15.4, 802.15.4-Pro, ZigBee, ZigBee-Pro, 868 SMA, 900 SMA, XSC SMA and Bluetooth. The signal range is up to 12 Km. depending on the protocols and the antennas used. For an inhabited environment (as it is our case) it is enough a 50-meter range and accordingly the 802.15.4 protocol is used, which is the one that less power requires.

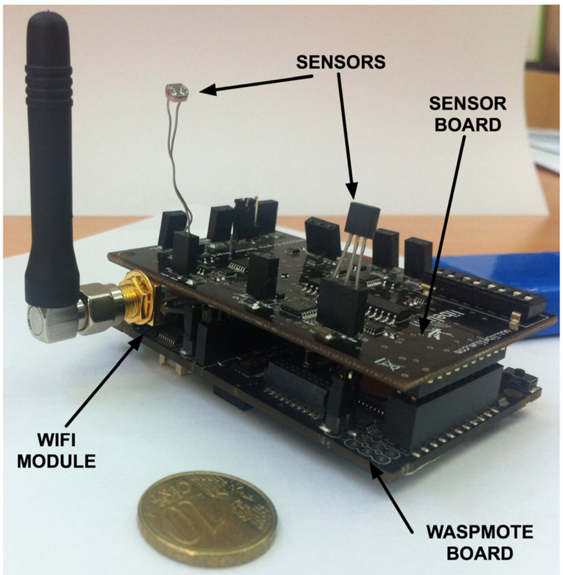

Figure 2: Waspmote-Sensor module. Three components are stacked: Waspmote board, XBee wireless module and sensor board. The blue element is a battery.

Waspmote hardware architecture has been specially designed to achieve extremely low consumption. Digital switches allow to turn on and off any of the sensor interfaces as well as the radio modules whenever they are not used. Also sleeping modes are available. For autonomous operation the board can be powered by rechargeable batteries (like in picture 2) or by solar panels, both provided by the company.

The sensor boards to be attached are designed depending on the area of operation: Agriculture board, general Events, Gases, Smart Metering, etc., and each board supports various sensors, such as temperature, luminosity, weight, bending, movement by infrareds, position based on hall effect, water presence, etc. The ATmega microcontroller governs the operation of the board -in an autonomous way- by executing a program which is developed by the user.

3.2 FPGA System

The second part of the proposed system addresses the Intelligent Agent. It is based on i) a FPGA in which the Neurofuzzy algorithms are implemented, ii) a JTAG port to program and debug the FPGA, and iii) a Serial Port (RS232) to communicate with the Wireless Network. Let us see in detail these three parts.

The FPGA (figure 3) is configured with a HW/SW architecture. It consists of a microprocessor (hardcore or soft-core), a RAM block to store the program to be executed by the microprocessor, one or several PWM-ANFIS hardware blocks and a RS232 peripheral controller. The number of FPGA resources required by this HW design depends basically on the amount of Neurofuzzy blocks to be implemented. For a small number (about 2 or 3) a low cost FPGA is enough.

The global operation of the FPGA system is as follows: the microprocessor reads periodically the RS232 port to collect data from the sensor network. These data are sent to the Neurofuzzy hardware blocks which calculate the various outputs. These outputs are then sent back to the microprocessor which in turn sends them to the actuators via RS232.

4 IMPLEMENTATION AND DISCUSSION

In order to test and verify the complete system we have implemented an Ambient Intelligent example. It consists of a system that controls the intensity of a floor lamp and the opening of a window in an inhabited environment, (particularly a room). The system takes as inputs the internal temperature, luminosity and humidity of the room and external

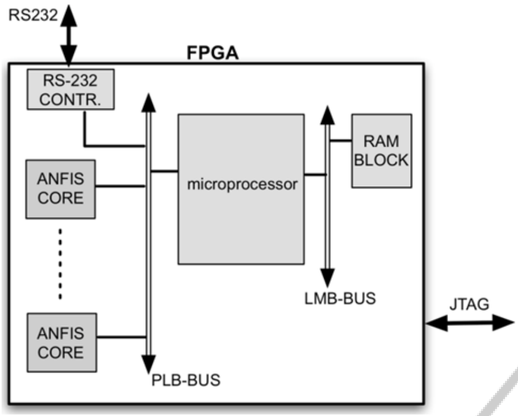

Figure 3: Scheme of the HW implemented on the FPGA.

temperature (all provided by the WSAN), and calculates -via the intelligent agent- the intensity level of the floor lamp and the position of the window: i.e. three positions: closed, semi-opened and full opened. For this purpouse, 2 Waspmote-Sensor modules are respectively placed inside and outside the room. Another Waspmote board to address the actuators (the floor lamp and the window) is also used.

4.1 Sensors and Actuators

One of the Waspmote-Sensor modules contains the sensors of temperature (MPC9700A termistor), humidity (808H5V5 capacitive-based sensor) and the luminosity (PDV-P9203 LDR). This module is placed inside the room. The other one, placed outside, contains an external temperature sensor (MPC9700A termistor).

The actuators are driving by another Waspmote board. In this case, no sensor board is attached; instead, we use the set of digital outputs that contains the board. Some of these digital outputs are connected to a D/A converter to provide an analog signal to the floor lamp regulator. In particular, the converter used is the DAC8228 from Analog Devices. Two other digital outputs are used to control the three window states: closed, semi-opened and full opened.

4.2 PWM-ANFIS Modelling

The system contains two PWM-ANFIS cores, one for the light-level response and another one for the window opening. The first one depends on the four input variables above mentioned, while in the second one the luminosity is not taken into account.

The intelligent agent is built up from linguistic information provided by a user, in the form of fuzzy IF-THEN rules. Hence, the user can express its habits and preferences in a very flexible (i.e. without restrictions) and natural way. Some of the rules formulated are for example the following:

***IF** tmp_int **IS** high **AND** tmp_ext **IS** normal **AND** humidity **IS** high **THEN** window is full-opened*

***IF** tmp_int **IS** very high **AND** tmp_ext **IS** very high **AND** luminosity **IS** high **THEN** light-level is very low.*

As a example, Figure 4 shows the surface generated by the fuzzy rules for the window positioning output with respect to the internal and external temperature.

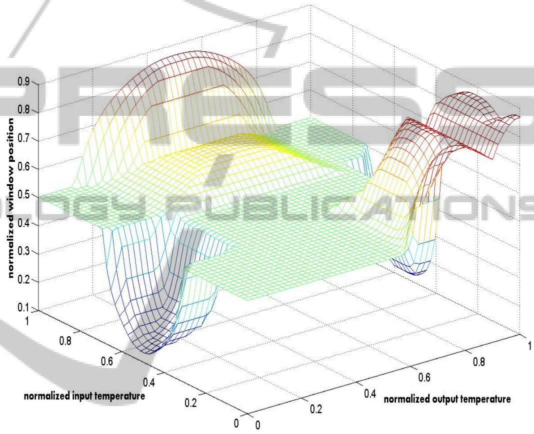

Figure 4: Window position output provided by the user-defined rule system.

However, a fuzzy rule inference system without restrictions implies a very complex hardware implementations which require large FPGA devices and make more difficult to provide real-time responses. To overcome this drawback we have used the PWM-ANFIS system previously explained. This system is trained from a set of samples provided by the above fuzzy rules system. Figure 5 shows, as example, the training error curve obtained during the learning process. In particular, the mean squared error (MSE) obtained between the system output and the desired output vs. the number of iterations of the algorithm is shown. As we can see, the values of the obtained errors are very small. So the PWM-ANFIS modellization is apropriate for this Ambient Intelligent Scenario.

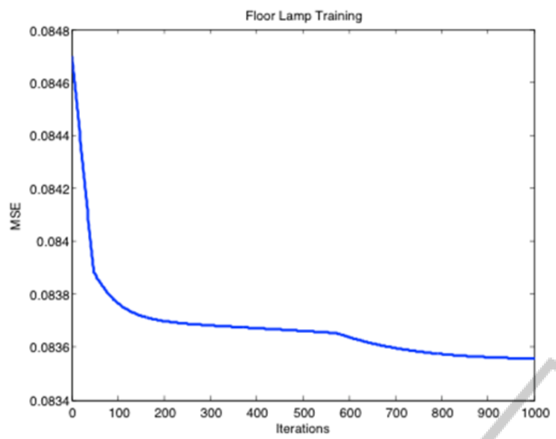

Figure 5: MSE training curve for the Floor Lamp model.

4.3 FPGA

The FPGA used is the Virtex 5 -xc5vsx50t- from Xilinx (Virtex 5, 2009). It features more than 8000 logic blocks, 4-Mbits RAM blocks and 288 Multipliers among other resources. Despite of its many resources, it is a medium size and medium cost device.

Inside this FPGA we have implemented the HW/SW architecture described in section 2: a Microblaze (soft-core from Xilinx), a RS232 controller to which a XBee is attached, a 64 Kbytes RAM module and the two PWM-ANFIS cores. To develop the system we have used the design tool ISE-Suite from Xilinx. After implementation the tool reports the following resource utilization: 40% of the multipliers, 12% of the RAM memory, 9% of logic elements and 7% of registers (i.e. Flip-Flops). As we can see, less than the half of the FPGA is used and therefore, more PWM-ANFIS could be implemented if we want to control more environmental parameters or devices. The frequency operation of this hardware implementation is 100 MHz.

The software counterpart is the program stored in the RAM module and executed by the Microblaze. This program occupies only a few Kbytes because the main operation of the Intelligent Agent is carried out by the PWM-ANFIS hardware modules. It only has to coordinate the data transfer between serial port and the hardware modules according to the wireless network protocol specifications. Also, it performs some changes in the data format to adapt these to the PWM-ANFIS algorithm.

5 CONCLUSIONS

In this paper, an embedded system for Intelligent Inhabited Environments, based on a WSAN and on an FPGA is presented. The WSAN has been carried out by means of the Waspmote platform, which is a modular, scalable and low power hardware platform that allows deploying easily a wireless sensor network.

In the system presented here, the WSAN takes measures from environmental parameters like temperature, humidity or luminosity and sends them to the FPGA, which is integrated in the wireless network thanks to a wireless communication module attached to it. The FPGA addresses an Intelligent Agent that processes the data of the sensors and provides a real-time response that acts over the environment via different actuators as an user would do it. The intelligent agent is based on ANFIS-type neurofuzzy systems for which a very efficient hardware implementation has been designed.

As an example of the proposal, a system that controls the intensity of a floor lamp and the opening of a window in an inhabited environment has been implemented. Aspects of this implementation are described in detail: hardware elements, sensors used, FPGA used, resources needed, execution time. This example shows the feasibility and the simplicity of the proposal and demonstrates that by integrating the low power WSAN and the FPGA-based Intelligent Agent, a small, low power, low cost high-performance intelligent environment system is achieved.

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