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Embedded System for the Regular Blood Pressure Monitoring

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Abstract. This paper presents the development of an embedded system for monitoring a patient's blood pressure, automating the inflation and deflation stages of the bracelet using an FPGA. The embedded system is based on the oscillometric method to get the patient's systolic and diastolic blood pressure. This method monitors the variations or oscillations of the pressure signal in the bracelet that is placed around the arm, to determine through the autocorrelation function the values of the above mentioned pressures. The system uses a digital pressure sensor for the data acquisition stage, an air pump and a mini solenoid valve. The system is implemented in the Xilinx's Microblaze soft-core processor configured in a Spartan 6 family FPGA. The Microblaze processor uses the processor local bus to communicate the peripherals. A IIC core is used to interface with the digital sensor and a GPIO core to control the air pump and a TIMER core to control the mini solenoid valve with a PWM signal. Finally, a UART core is used to send data to a personal computer where an application server is implemented. This server allows remote monitoring of pressure sensor information by medical staff.

Keywords: FPGA, embedded system; health care.

1 Introduction

The vital signs are clinical parameters that reflect the physiological status of the human organism, and essentially, they provide data which will set the standards for evaluating the homeostatic state of the patient, showing his actual health condition as well as the changes or evolution, either positively or negatively. Vital signs include: temperature, breathing frequency, heart rate and blood pressure, among others.

Nowadays, vital and biomedical signs cover a wide spectrum of applications in different contexts, so that it has been a recurring research subject during the last decade [1-5]. Currently systems designed for vital sign monitoring which use different technologies exists.

Some researchers [2,3,5] have proposed to use microcontroller based technology to monitor several vital signs like heart rate, breathing, among others. In [4] an ARM processor based embedded system is used with a Linux operating system so as to monitor the electrocardiographic signal (ECG) of a patient.

The proposed system is an embedded system which uses a field programmable gate array (FPGA) to monitor blood pressure (BP). Blood pressure is the force the blood exerts against the arterial walls. Every time the heart beats, it pumps blood towards the arteries, producing a pressure that is measured in mmHg. This pressure is made up of systolic blood pressure (SBP), the first figure, which is the maximum value the circulatory system registers when the heart contracts to pump blood to the arteries and deliver it to the whole organism; and diastolic blood pressure (DBP), the second figure, which represents the minimum value the artery register when the heart relaxes to be filled with blood again.

Hypertension or High Blood Pressure (HBP) is a sustained elevation of SBP, DBP or both which affects a considerable part of adult population, particularly the elders. The HBP is defined by the continuous presence of equal or greater than 140 mm Hg SBP figures, equal or greater than 90 mm Hg DBP figures or both [6].

In care practice, there are several different measurement methods that can be classified as: capillary color change, through pulse, auscultatory, oscillometric, doppler, intra-arterial or forthright. Among these, the most used method is the auscultatory one given that it is a non-invasive external method, the most accurate one and the most studied and researched. Notwithstanding, during recent years electronic devices for BP measurement are being introduced in everyday clinic practice. Nowadays, these electronic devices are preferred due to their easiness, comfort of use and to avoid the observer bias (it is the observer himself one of the main sources of inaccuracy in BP measurement) [7].

The proposed embedded system uses the oscillometric method as a base to obtain the SBP and DBP of the patient. The difference with the previous one is that this method monitors the variations or oscillations of the pressure signal on the cuff that goes around the arm to determine, through the obtained signal analysis, the values of the aforementioned pressures. In other words, while the cuff is being deflated from a value above the SBP, the artery walls begin to vibrate or oscillate as the blood flows through the partially occluded artery and these vibrations are captured by the sensor that monitors the pressure on the cuff. As the pressure keeps dropping, the oscillations increase until a maximum amplitude and then they decrease until the cuff is totally deflated and the blood flow returns to normal.

The pressure on the cuff during the maximum oscillation point normally corresponds to the mean arterial pressure (MAP). The point above the MAP, in which the oscillations begin to quickly increase in amplitude corresponds to the SBP. The point in which the oscillations variation decreases most abruptly corresponds with the DBP.

2 Proposed System Architecture

The embedded system is constituted by three modules, which are:

- Data acquisition and control.
- Embedded system
- Data display software.

The system architecture is shown in Fig. 1. In the system, the patient's arterial pressure signal acquisition is done through a digital sensor afterwards, the signal is sent to a soft-core processor synthesized on a FPGA where is processed and sent to a data display software on a personal computer.

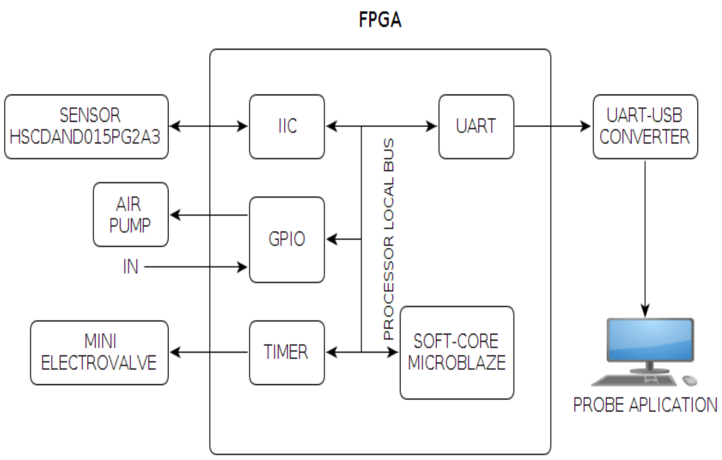

Fig. 1. System Architecture.

2.1 Data Acquisition and Control

The data acquisition module oversees obtaining the blood pressure signal of a patient in a digital for so it can be processed by the FPGA. This module is constituted by the following elements:

1.– Pressure digital sensor model HSCDAND015PG2A3 form Honeywell manufacturer [8]. It measures manometric pressure, also known as Gauge, is completely calibrated and compensated, handles a measuring range from 0 to 15 psi (equivalent to 0 to 775.72mmHg). Particularly, this prototype can detect blood pressure in a range from 0 to 400 mm Hg (equivalent to 0 to 7.7345 psi). It has a 14 bits analog-digital converter integrated, requires an input voltage of 3.3V and sends data through the Inter Integrated Circuit Bus (IIC) in the embedded system architecture. Furthermore, it has a total band error (TBE) of 1%, namely ±7.7mmHg. The sensor has the transfer function shown in equation 1. With this function, the pressure applied to the sensor can be determined based on the output value of the sensor:

$$Output = \left(\frac{Output_{max} - Output_{min}}{P_{\max} - P_{\min}} \right) * \left(P_{applied} - P_{\min} \right) + Output_{min} , \quad (1)$$

where:

$Output_{max}$: Maximum output value (90 % de 2^{14}).

$Output_{min}$: Minimum output value (10 % de 2^{14}).

$P_{\max}$: Maximum supported pressure (15 psi).

$P_{\min}$: Minimum supported pressure (0 psi).

$P_{applied}$: Pressure applied to the sensor.

$Output$: Output value of the sensor.

2.– Standard size nylon cuff.

3.– Air pump that requires an input voltage of 6V and 460 mA of current. It handles a maximum pressure of 400 mm Hg, for the automatized inflation of the cuff stage. The relevance of the inflation stage lies in that is in this stage where the SBP of the patient can be immediately determined. This happens when the brachial pulse disappears, namely the artery is completely occluded by the cuff. The pressure value registered in the cuff by the sensor corresponds to the SBP. Nevertheless, due to time constraints, no algorithm to identify this event was made in the present work. For the time being the cuff is always inflated until 160 mm Hg followed by the deflation stage.

To handle the air, pump a General Purpose Input Output (GPIO) peripheral is used in the embedded system architecture. For this reason, a power stage was designed using a 4N30 optocoupler to avoid damaging the FGPA. The power stage is shown in Fig. 2.

Mini air electrovalve that requires an input voltage of 6V and a current of 250 Ma, it allows for a maximum escape speed of 88.3 mm Hg/s for the automatic cuff deflation stage. Given the case of the electrovalve the use of a pulse width modulated (PWM) signal is proposed to control the output air flow, ensuring the output don’t go over the 3mm Hg/s ratio which is indicated by norm. To manipulate the mini electro valve a timer is used on the embedded system architecture. Taking that into account, is necessary to remove the optocoupler and use solely the transistor to obtain the current needed to activate de valve. This is because the optocoupler doesn’t support an input current with a frequency higher than 1 KHz. From this frequency value, the optocoupler always provides a logical 1 as output, completely activating the mini electrovalve resulting on an immediate deflation of the cuff at a higher ratio than 3 mm Hg/s. The power stage is shown in Fig. 3.

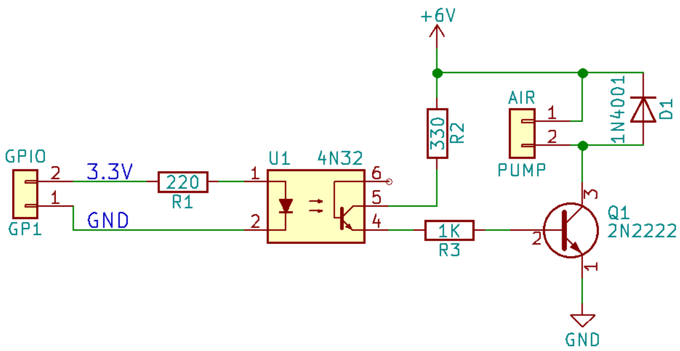

Fig. 2. Power stage for air pump.

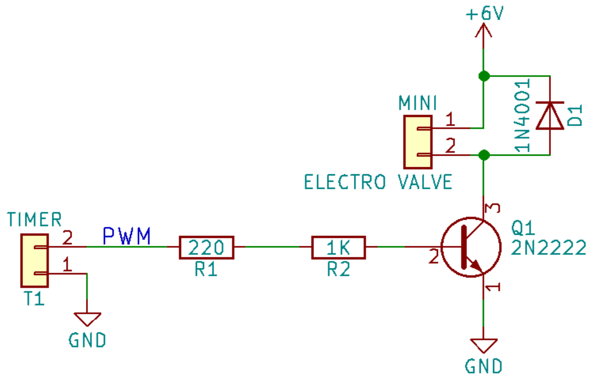

Fig. 3. Power stage for mini electro valve.

2.2 Embedded System

The embedded system has a Spartan 6 familiy, XC6SLX16 model Xilinx FPGA [9] as the processing unit with the Nexys 3 [10] development board from Digilent Inc. It has a 576Kb Block RAM memory, enough to embed the application on the Microblaze soft-core processor, responsible of all the calculations done in the system. The development board Nexys 3 offers its development environment (software) to configure the embedded system and imprint it on the board. The environment is the Xilinx Design Tools software that includes the Environment Development Kit (EDK) which on turn, is composed by Xilinx Platform Studio (XPS) to implement the necessary hardware configuration for the embedded system and by Xilinx Software Development Kit (SDK), which is used to link the hardware system created with XPS with the software application (usually in C/C++ language), thus creating a tailormade system.

The embedded system is formed by the following elements:

1.– Embedded system architecture: One of the prime advantages of working with a hardware reconfigurable FPGA board is that, as the name indicates, it allows the user to choose the hardware modules that he wishes to implement on his embedded system. The embedded system is constituted by the following modules:

a. GPIO core Driver to control the activation and deactivation of the air pump.

b. Timer/Counter core Driver in charge of producing the PWM signal to control the activation and deactivation of the mini electrovalve.

c. IIC Driver to communicate the blood pressure sensor with the board. The sensor has an output of up to 4 bytes (data) depending on the options it has been configured with, according to the application needs. Under any circumstances, the first two bytes correspond to pressure values, while the third and fourth bytes correspond to a temperature value (that is optional to use). The sensor has an address equal to 0X28 and is configured at a standard speed of 100 KHz. The reading format is shown in Fig. 4.

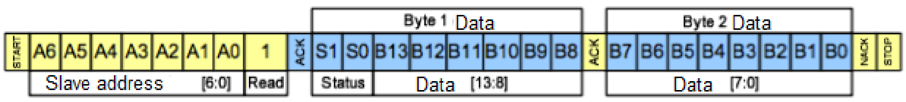

Fig. 4. Sensor reading format.

a. UART Driver to send the data processed by the microblaze sof.core for its storage and subsequent consultation.
b. PLB bus Driver that communicates the GPIO, Timer/Counter, IIC and UART modules with the microblaze softcore.
c. Driver for the data and instruction memories DLMB and ILMB of the microblaze softcore.

3 Processing Algorithms

The main problem of the oscillometric method consists in the detection and amplification of the oscillatory pulses that are generated in the cuff during the deflation stage, starting from the data collected form the sensor, as well as the subsequent analysis of these pulses to calculate SBP and DBP.

There are algorithms sensitive to pulse pressure difference and to artery stiffness, however, most of them are well kept as commercial secrets, so that the exact SBP and DBP attainment using the surrounding curve of the oscillations that occur on the cuff during the deflation stage continues being an open problem in biomedic engineering [11]. Given that, we developed our own algorithm on an experimental way.
In this case the sensor recollects data during the cuff's inflation and deflation stages and sends it to the FPGA board at a transfer speed of 100 KHz. The cuff is inflated until it reaches a 160 mmHg pressure which indicates that, at the present time, the cuff can only measure the BP of patients that hace degree 1 or lower HTA, this is due to the lack of an algorithm to determine when the artery becomes totally occluded during the inflation stage, the pressure when this event is detected corresponds to the SBP.

Using the collected data, the oscillations that occur on the cuff during the deflation stage are detected. In this case, this is done by the autocorrelation function calculation every 64 sensor reading, according to equation 2:

$$rxx[n] = \frac{1}{N} \sum_{m=0}^{N-1-|n|} x[m]x[m+|n|] . \quad (2)$$
$$n = 0,1,\ldots N-1$$

The algorithm shown on Fig. 5 and Fig. 6 describes the pseudocode used in this system to determine the SBP and DBP of a patient. As input, it takes at most 3000 readings from the pressure digital sensor. The algorithm begins with de global variables declaration, an initialization stage of: FPGA buttons, GPIO bus and PWN pulse.

The algorithm on Fig. 5 starts with an infinite loop where an auxiliary variable *i* is declared to control the samples count, as well as a *stop* flag which is used to distinguish between inflation and deflation stages. Line 16 verifies whether the start button has been pressed, in that case, the mini electrovalve is closed and a loop from 0 to the maximum number of samples is began. Both during the inflation and deflation stages, the sensor reads the pressure of the cuff and stores the data on the global array *muestras*, on the next line the *i* value is increased. When the value of this variable is equal to 64, it is proceeded to calculate the autocorrelation of the samples, the value of *i* is reset, then it is tested if the last *dato* is less than or equal to 55 and if the *paro* signal is different from 1 (this means it is on the deflation stage). If this this positive the the loop is broken and is followed by the calculation of the BP of the patient. In case *i* is different from

64, it is checked whether *dato* is less than 160 and *paro* is equal to 1 (this means it is on the inflation stage), hence the air pump is activated, otherwise the *paro* signal is set to 0 followed by the deactivation of the air pump, the mini electrovalve is opened to 11.69%, decreasing on a .80% the PWM work cycle every 20 mm Hg.

Algorithm 1: Procedimiento general para calcular PAS y PAD.

```
Datos: Máximo 3000 lecturas del sensor.
Resultado: PAS y PAD del paciente.
Variables Globales:
        indice ← 0
        TOTAL_MUESTRAS ← 3000
        N ← 64
        muestras[N]
        promedios[TOTAL_MUESTRAS/N]
        valorMaxAuto[TOTAL_MUESTRAS/N]
begin
    Inicialización:
            Botones de la FPGA
            Bus GPIO para controlar bomba de aire
    /* 250 Khz con ciclo de trabajo al 50 % */
            Pulso PWM para controlar mini-electroválvula
    while True do
        i ← 0
        paro ← 1
        if botonInicio = 1 then
            Cerrar mini-electroválvula
            for j ← 0 to TOTAL_MUESTRAS do
                leerSensor(dato)
                muestras[i] ← dato
                i ← i + 1
                if i = N then
                    calcularAutocorrelacion()
                    i ← 0
                    if dato <= 55 y paro ≠ 1 then
                        break
                /* Etapa de inflado del brazalete
                   */
                if dato < 160 y paro = 1 then
                    Activar bomba de aire
                /* Etapa de desinflado del
                   brazalete                        */
                else
                    paro ← 0
                    Desactivar bomba de aire
                    Abrir mini-electroválvula al 11.69 %
                    Disminuir 0.80 % al ciclo de trabajo de
                    PWM cada 20 mm Hg
            calcularPresionArterial()
            paro ← 1
```

Fig. 5. General procedure for evaluate SBP and DBP.

```
Función: calcularAutocorrelacion()
/* Este arreglo contiene los 64 datos
   obtenidos por el sensor.                         */
Datos: muestras[N]
Resultado: Valor promedio de las 64 muestras y valor máximo
           de la Autocorrelación.
promedios[indice] ←Obtener el promedio
/* Calcular la Autocorrelación de las 64
   muestras.                                        */
b ← 0
for m ← 0 to N do
    rxx ← 0
    for n ← 0 to N − m do
        rxx ← rxx + ((muestras[n] − promedios[indice]) ∗
        (muestras[n + m] − promedios[indice]))
    resultado[b] ← rxx
    b ← b + 1
valorMaxAuto[indice] ← Valor máximo de resultado[N]
indice ← indice + 1
```

Fig. 6. Autocorrelation function.

4 Data Display Software

The data display software consists of a test web program where the medical personnel in charge of reading the BP measurements of the patients can register. Said personnel can register new patients on the database using the same web site, as well as generate reports about the performed measurements. The use case for the medical personnel is shown on Fig. 7 and the main screen of the system is shown on Fig. 8.

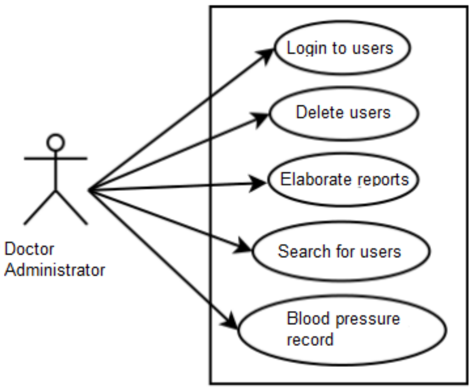

Fig. 7. Use cases for medical staff.

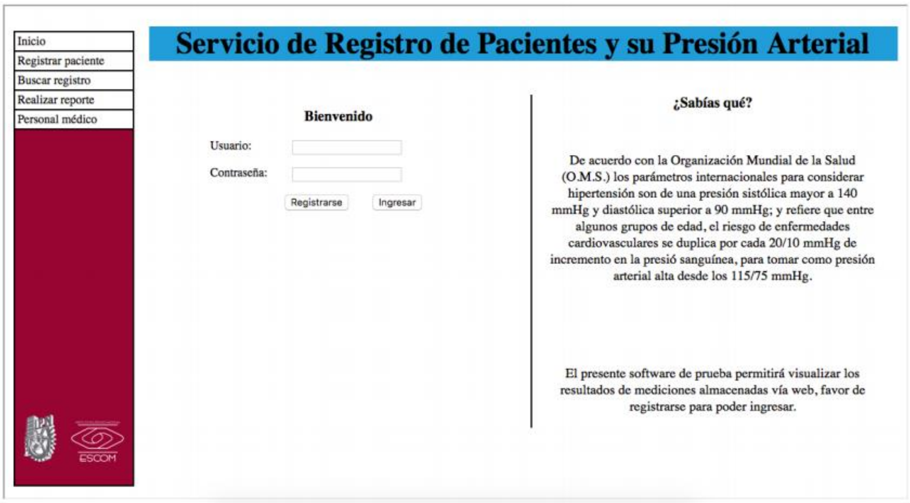

Fig. 8. Main system screen.

5 Testing and Results

The hardware configuration of the embedded system was done using *Xilinx Platform Studio (XPS).* Firstly, the required controllers for the FPGA Nexys 3 were selected, the number of processors to be used, as well as the Soft-core Microblaze and the GPIO, UART, Timer/Counter and I2C cores. Secondly, space on memory was asignated, then the input/output signals were established linking every one of them to the FPGA pins. Finally, the project was compiled to generate a bitstream file. The embedded system is shown on Fig. 9.

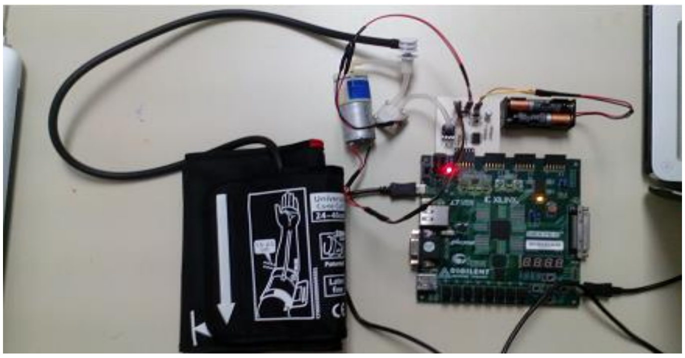

Fig. 9. Final prototype of the embedded system.

The software configuration was done using Xilinx Software Development Kit (SDK). In first place, it is necessary to import the bitstream file to create the support files for each core. Then a C language project was created where a program which implements the previously mentioned pseudocode was created. After that, the project was compiled so as to create a *download bit* output file. This is the file which is burned on the FPGA y grants functionality to the embedded system.

Considering that the method used is the oscillometric one, the deflation stage is of vital importance given that it is during this stage where the pressure oscillations present on the cuff, therefor deflation test were done to the mini electrovalve, varying the PWM pulse frequency of the FPGA as well as its work cycle, being able to prove that with a 250 KHz frequency and a 11.69% work cycle the air was expelled properly from the cuff but only on the 160 to 120 mm Hg range. This is because the pressure on the cuff decreases gradually however the mini electrovalve continues letting the air flow at a steadfast rate. Therefore, the work cycle was reduced by a 0.8064% every time the pressure on the cuff decreased by 20 mmHg beginning at 120 mmHg given that the mini electrovalve is activated on low.

Table 1. Measurement results for 25 people.

No.	Valor del Sistema (VdS) (PAS / PAD) (mm Hg)	Valor del Baumanómetro (VdB)(PAS / PAD) (mm Hg)	Error Absoluto (|VdS-VdB|) (mm Hg)	Error Relativo (|VdS-VdB| /VdS)
1	115/ 67	120 / 68	5/1	4.3 % / 1.49 %
2	123/ 73	123/ 69	0/4	0 % / 5.47 %
3	137/ 73	129/ 73	8/0	5.83 % / 0 %
4	117/ 71	122/ 69	5/2	4.27 % / 2.8 %
5	117/ 70	117/ 66	0/4	0 % / 5.71 %
6	130/ 65	137/ 77	7/12	5.38 % / 18.46 %
7	125/ 80	119/ 67	6/13	4.8 % / 16.25 %
8	137/ 79	137/ 77	0/2	0 % / 2.5 %
9	113/ 65	106/ 60	7/5	6.19 % / 7.69 %
10	100/ 60	100/ 62	0/2	0 % / 3.33 %
11	112/ 78	116/ 72	4/6	3.57 % / 7.69 %
12	127/ 84	120/ 68	7/16	5.83 % / 19.04 %
13	129/ 81	124/ 78	5/3	3.87 % / 3.7 %
14	114/ 75	115/ 77	1/2	0.87 % / 2.66 %
15	122/ 80	119/ 74	3/6	2.45 % / 7.5 %
16	124/ 68	125/ 78	1/10	0.8 % / 14.7 %
17	119/ 83	118/ 74	1/11	0.84 % / 13.25 %
18	115/ 65	119/ 81	4/16	3.47 % / 24.61 %
19	105/ 68	102/ 69	3/1	2.85 % / 1.47 %
20	111/ 67	111/ 75	0/8	0 % / 11.94 %
21	137/ 80	136/ 77	1/3	0.72 % / 3.75 %
22	111/ 81	111/ 69	0/12	0 % / 14.81 %
23	123/ 67	120/ 75	3/8	2.43 % / 11.94 %
24	122/ 80	119/ 74	3/6	2.45 % / 7.5 %
25	111/ 73	117/ 73	6/0	5.4 % / 0 %

Also, a full opening signal was set when the cuff presented a pressure less than or equal to 55 mm Hg because after over 50 test we observed that if the PWM was left until the cuff deflated completely, the SBP and DBP calculation was not done correctly. Likewise, even though in theory the cuff has to be deflated at a 3 mm Hg/s rate in order to obtain a correct blood pressure measurement, in practice it was observed that the

OMRON commercial baumanometer model HEM-742INT, which was used for comparisons, deflated the cuff at a 5 mm Hg/s rate. On this embedded system, the deflation stage was done within a range of 20 to 25 seconds at a 4.5 mm Hg/s rate.

There were made 25 measurements to the same amount of people with the OMRON electronic baumanometer and this embedded system. This baumanometer was taken as a reference value because the WHO and the Panamerican Health Organization (OPS, given its Spanish acronym) establish that well-kept and properly calibrated and validated mercury free tensiometers or baumanometers provide an accuracy commensurable to non-mercury free devices [12], in this case the OMROM baumanometers are distinguished for following strict calibration protocols and for sticking to several international standards (ANSI and ISO), this model in particular is validated by the British Hypertension Society and has an accuracy of ±3 mm Hg [13]. The results are shown on Table I. The absolute and relative errors of each measurement were calculated, the SBP presented a variation between 0 and 8 mm Hg which corresponds to 0 and 6.2% relative error and the mean SBP relative error was 2.65%. On the other side, the DBP presented a wide absolute error margin going from 0 to 16 mm Hg which correlates to relative errors between 0 and 24.7%, with a 8.39% mean relative error.

6 Conclusions

Despite being on the 21st century, Mexico displays severe lateness on health care, mainly as a consequence of overpopulation and lack of medical personnel to provide satisfyingly the human resources requirements of this area, without mentioning that in most administrative and auscultation processes which are carried out manually, the presence of medical personal is needed to perform it. In the search of reducing the lack of health care problem in the social context, arises the need for the development of new methodologies that incorporate technology.

The present work was able to design and implement an embedded system on a FPGA to monitoring the blood pressure of a patient, automatizing the data acquisition from the digital sensor controlling an air pump for the cuff inflation stage and a mini electrovalve controlled via a PWM signal which allows for regulating the cuff's deflation rate. The values of the work cycle and frequency were obtained in an experimental way.

An algorithm was proposed to calculate the blood pressure on the embedded system taking the oscillometric method as foundation and performing the autocorrelation of the samples taken by the sensor. Following the same line, a program was designed and implemented to allow the storage of doctors and patients register information, as well as the blood pressure data received from the FPGA and generate reports on this.

By using reconfigurable technology, we can customize the architecture to fit our needs. The proposed system allows an easy addition of other vital signs to the architecture, along with a different amount of them on contrast to the systems that use microcontrollers, DSP or processors (ARM, MIPS, etc) with a predefined architecture.

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